Unit 21
HTS accelerator magnets

Steve Gourlay and Soren Prestemon

Lawrence Berkeley National Laboratory (LBNL)

Outline

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4. Bi-2212
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5. ReBCO
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6. Supporting Technologies
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    3. Structure Materials
7. Current Programs
8. Next Steps in Development
9. Conclusions

New materials, new applications
High Temperature Superconductors

Generally, steady improvements lead to new applications . . .

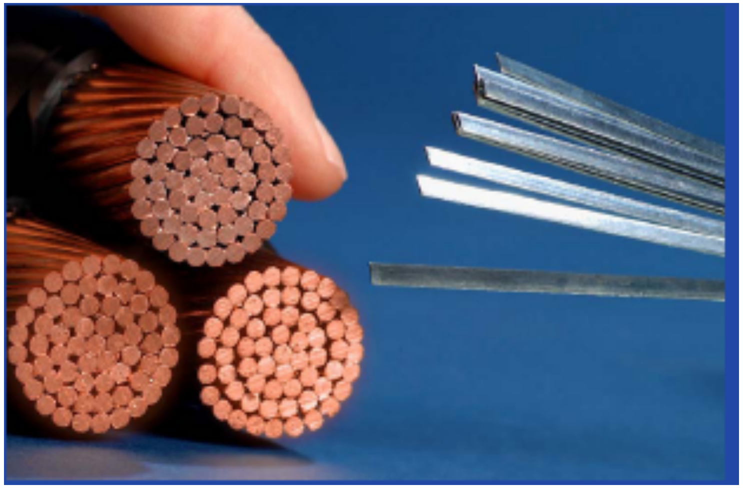
But, there are big leaps too.

- 1986 – discovery of HTS by Bednorz and Müller (BSCCO)
  - **Generated excitement, activity**
  - **Nobel prize in 1987**
- Discovery of YBCO in 1987 by Paul Chu, U. of Houston
  - **Superconductivity in LN_2 range**

Exotics with T_c up to 160K

Exotic, but potential drives development

- High Temperature Superconductor (HTS)
  - **Bi 2212**
    - **Round strands in long lengths**
    - **React and wind only option for large coils?**
  - **Bi 2223**
    - **Tapes in long lengths**
  - **YBCO**
    - **High critical current but length is a problem**



150X capacity of equivalent copper

And MgB_2 (2001) and FeSC (2006)

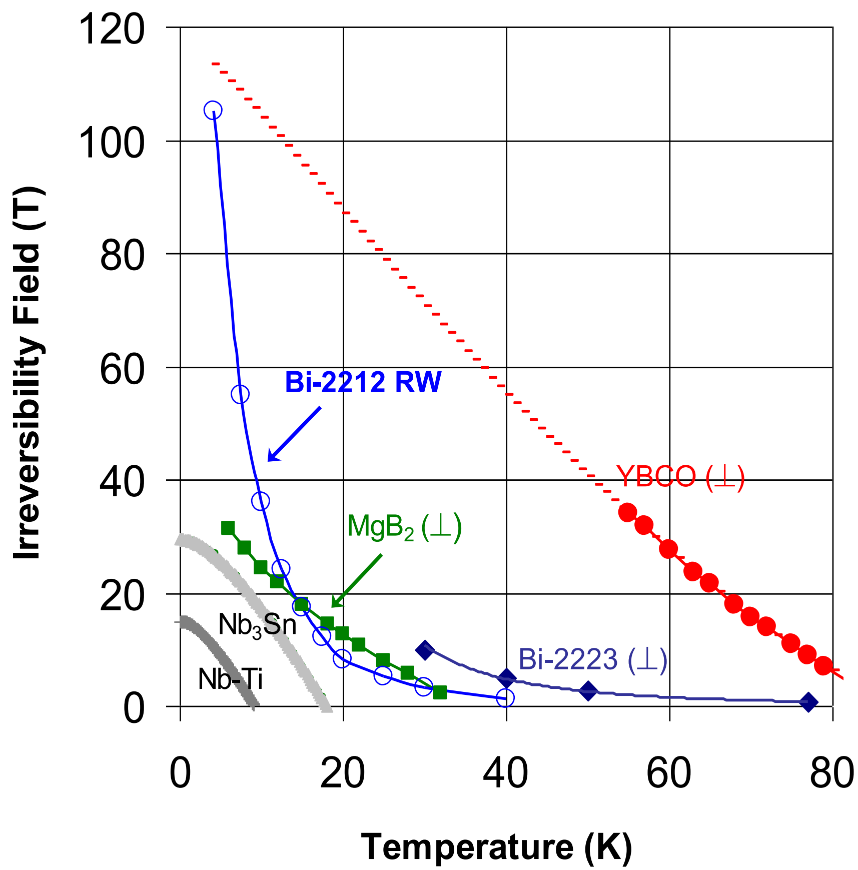
Snapshot of Conductor and Magnet Technology

- LTS
  - 27 km of Nb-Ti accelerator magnets at near operational potential
  - First Nb_3Sn accelerator magnets to be installed in LHC
  - LHC Quads on the way
  - High field solenoids
  - Fusion magnets

- HTS
  - MgB_2 links for LHC upgrade
  - Power cable demos
  - Power leads
  - > 1 GHz NMR magnets
  - And – 32T solenoid!
  - Several active R&D programs

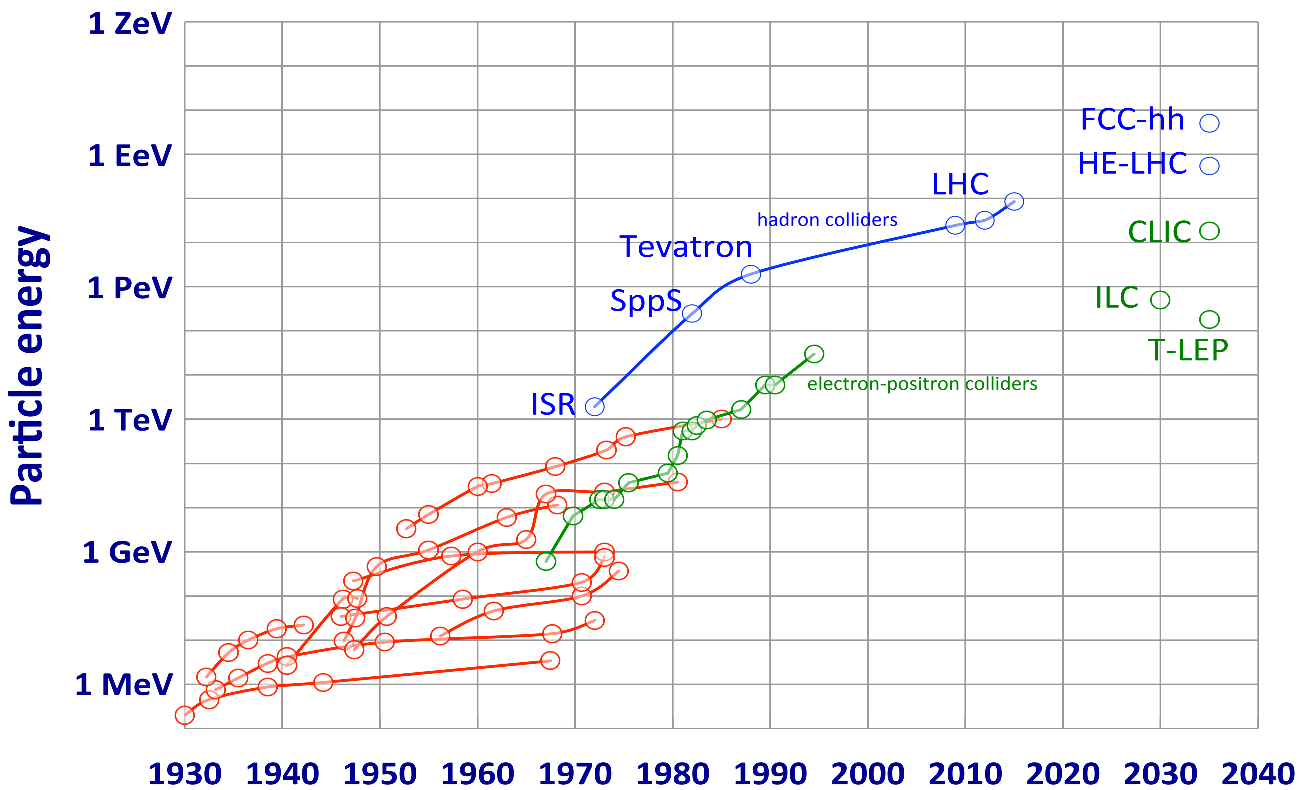
No accelerator magnets (yet)

Basic Properties: Field vs Temperature



(Courtesy of J. Jiang, FSU)

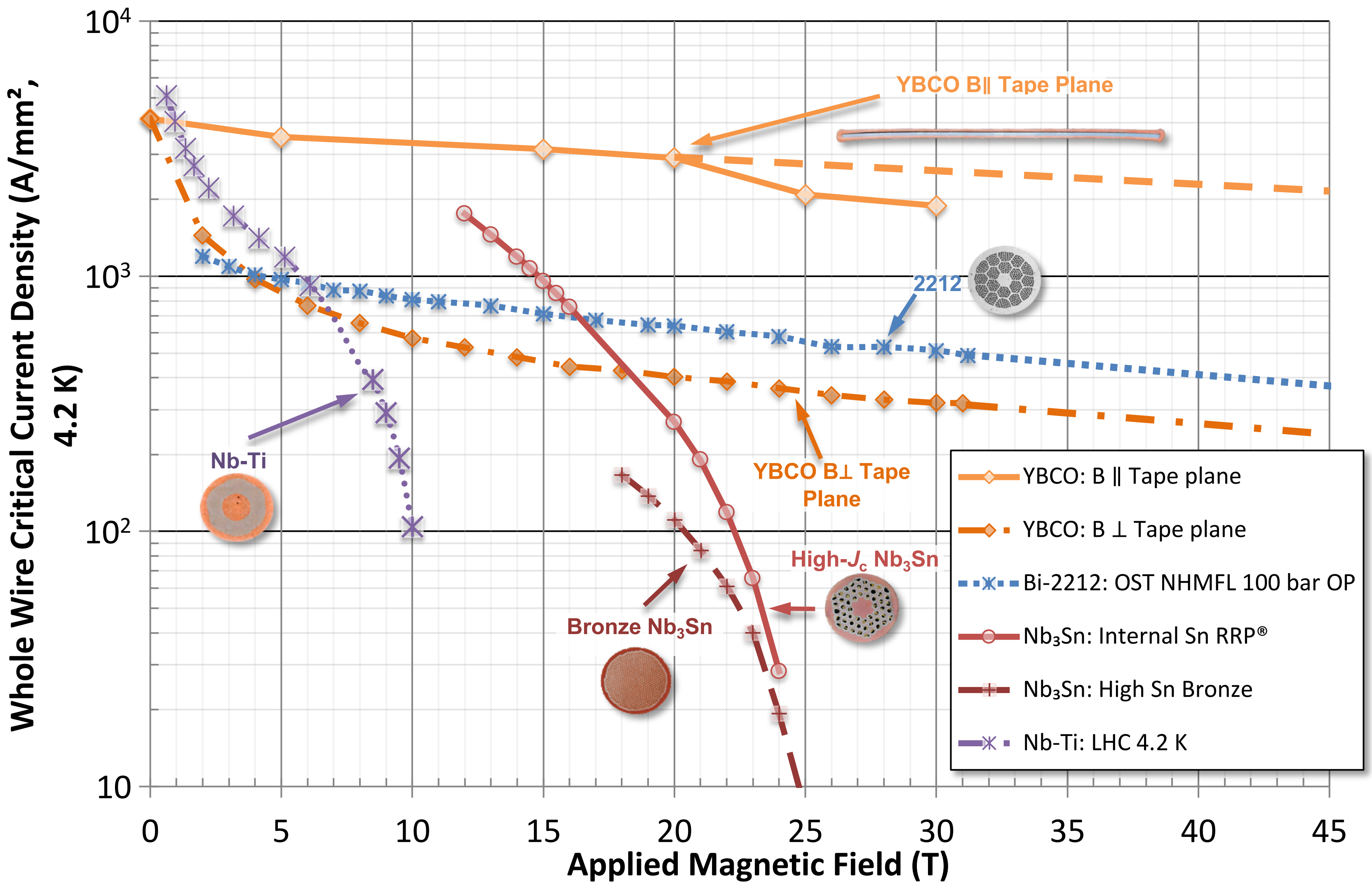
An Historic Need for High Field



Livingston plot of particle energy (in the laboratory reference frame, fixed target equivalent), where blue refers to hadron colliders and green to lepton colliders.

L. Bottura, CERN

Field Realm of HTS



Review: LTS is not perfect

- Let's say that Nb-Ti technology is maxed out.
  - Fields up to 9 - 10T
  - Training
  - Required margin
- What are the challenges/limits with Nb_3Sn?
  - Practical fields limited to 16 T or less (most likely less)
  - Strain sensitivity
  - More training
  - Required margin
  - Does not consistently reach short sample (see "training")
- HTS may eliminate some of these problems but generates others

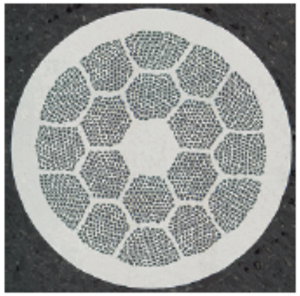
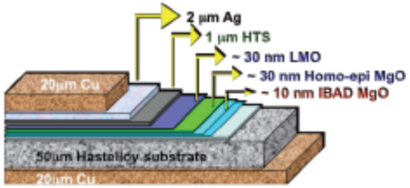
HTS Potential and Challenges

- Advantages . . .
  - High Field
  - High J_c (J_e's comparable to or exceeding LTS at low temperature)
  - High stability (no training!?)
  - Can operate in forced-flow helium gas at 20 – 30K, greatly reducing the complexity and cost for operation at the expense of J_c
    - Low/high temp operating depends on application
  - No heat treatment required (ReBCO)
    - Puts more of the manufacturing risk up front

- . . . come with some Disadvantages
  - Cost
  - Quench detection and magnet protection (the downside of stability)
  - Manufacturability
    - ReBCO – deposition processing
    - Bi-2212 coil manufacturing
  - Magnetization ((ReBCO)
  - Subject to degradation (ReBCO)
  - Strain sensitivity (Bi-2212)

Plus some other engineering challenges

Pros and Cons of Bi-2212 and REBCO

Conductor	Pros	Cons
2212 	• Round, multifilamentary, twisted wire with isotropic J_c insensitive to field orientation. • Rutherford cable readily made. • D_{eff} at ~100 um but with low J_c at low field and therefore relevantly small persistent current effect • High J_c, high *RRR*	• Expensive - \$155/kA-m at 4.2 K and 20 T. • Small market beyond HEP (>1.3 GHZ NMR) • Strain sensitive. • Weak mechanical properties; poor capability for Rutherford cables to handle transverse stress • Challenging heat treatment - high J_c achieved with high pressure treatments at 890C; narrow processing windows
REBCO 	• High J_c • Strong ability to handle axial stress • Broad applications beyond HEP • Multiple vendors and conductor design. • Potentially cheap in 10-20 years.	• Expensive - \$234/kA-m at 4.2 K and 20 T. • Mono-core tape with strong J_c anisotropy – high magnetization effects. • Easy delamination. • Long-length nonuniformity – km conductor cut into 100-300 m pieces.

Quench Detection and Magnet Protection

- Still a tough nut to crack
  - Have to deal with success
  - Higher current density increases energy that may exceed the coil's heat capacity – add more copper?

- Several solutions close to demo that could provide early detection – key to magnet protection.

- But . . . Totally different environment
  - The only reasons for an HTS magnet to quench is because it exceeded its critical current or temperature increase due to cryo failure or beam induced heat load.

- However, cryo failure gives sufficient warning and transient beam induced heat loads are probably not enough to initiate quench – unless it's catastrophic (then you're screwed)

- Another mitigation might be to have rather poor cooling, allowing more time to detect the quench

Quench Detection Issues and Methods

- Issues
  - Stability results in slow propagation of normal zone
  - Traditional voltage-based detection may not be sensitive enough (especially in relatively noisy environment of an accelerator)
  - The consequent high energy density may exceed the heat capacity of the coil and adding more copper is not considered a good option. (decreases J_e)
- Methods
  - Voltage Taps
    - Intrusive (for all magnets) – create shorts, coil failures
    - Difficult to implement in complex magnet geometries (multiple layers)
    - May work for HTS in some cases (no more about that here)
  - Fiber-Optic
  - Acoustic
  - Capacitance probes
  - Average E-field

Fiber-Optic Quench Detection

- Quench detection system based on temperature detection by means of optical fibers. The main idea is to directly detect the coil temperature, rather than relying on quench detection via voltage growth by using Rayleigh backscattering. Rayleigh back-scattering interrogated optical fibers (RIOF) offer a much greater spatial and time resolution, virtually limited only by data acquisition speed and real time data processing capability. One other great advantage of RIOF is that it relies on the use of simple commercially available fibers.

- Potential
  - Early detection of temperature onset and fast discharge, eliminating quench and its consequences in superconducting magnets
  - Temperature raise can, indeed, be detected before it has time to drive the coil — or a portion of it — to normal state, allowing discharging the magnet before a quench is actually developed.

- Challenges
  - Vulnerability of fiber to damage during winding, assembly and cooldown
  - Scalability to large scale use

F. Scurti, S. Ishmael, G. Flanagan, and J. Schwartz, "Quench detection for high temperature superconductor magnets: a novel technique based on Rayleigh-backscattering interrogated optical fibers," Superconductor Science and Technology, vol. 29, p. 03LT01, 2016.

W.K. Chan, G. Flanagan, J. Schwartz, Spatial and temporal resolution requirements for quench detection in (RE)Ba2 Cu3 Ox magnets using Rayleigh-scattering-based fiber optic distributed sensing, Supercond. Sci. Technol. 26 (2013) 105015 [Online]. Available: http://dx.doi.org/10.1088/0953- 2048/26/10/105015.

F. Scurti, S. Sathyamurthy, M. Rupich, J. Schwartz, Self- monitoring SMART (RE)Ba2Cu3O7-x conductor via integrated optical fibers, Supercond. Sci. Technol. (2017) [Online] Available: https://doi.org/10.1088/1361- 6668/aa8762.

Passive and Active Acoustic Quench Detection (Eigen Frequency Thermometry)

- You've seen how this technique works. It appears to have good potential for implementing in HTS magnets.

- Unique aspect of HTS is that quenches are uniquely caused by local heating. Either a defect or just the conductor limit. (So we think now)

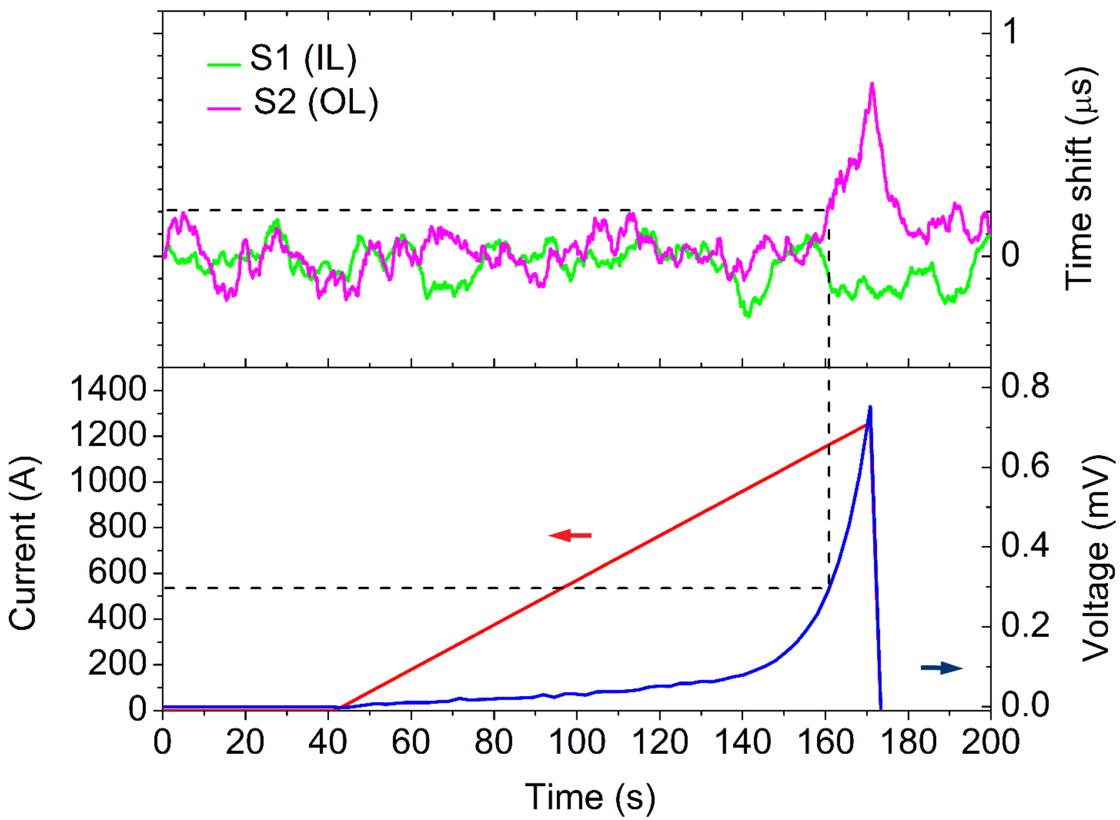
- Experiments so far on YBCO tapes, CORC® dipole and Bi-2212 racetrack have been encouraging.

- The technique is undergoing further improvements and exploring the potential of using multiple sensor arrays for quench localization.

M. Marchevsky, G. Sabbi, H. Bajas, S. Gourlay,"Acoustic emission during quench training of superconducting accelerator magnets," *Cryogenics* 69, 50 (2015), DOI: 10.1016/j.cryogenics.2015.03.005

M. Marchevsky, Quench detection for HTS conductors and coils using acoustic thermometry, https://escholarship.org/uc/item/65v2946m.

Example: CORC® Dipole



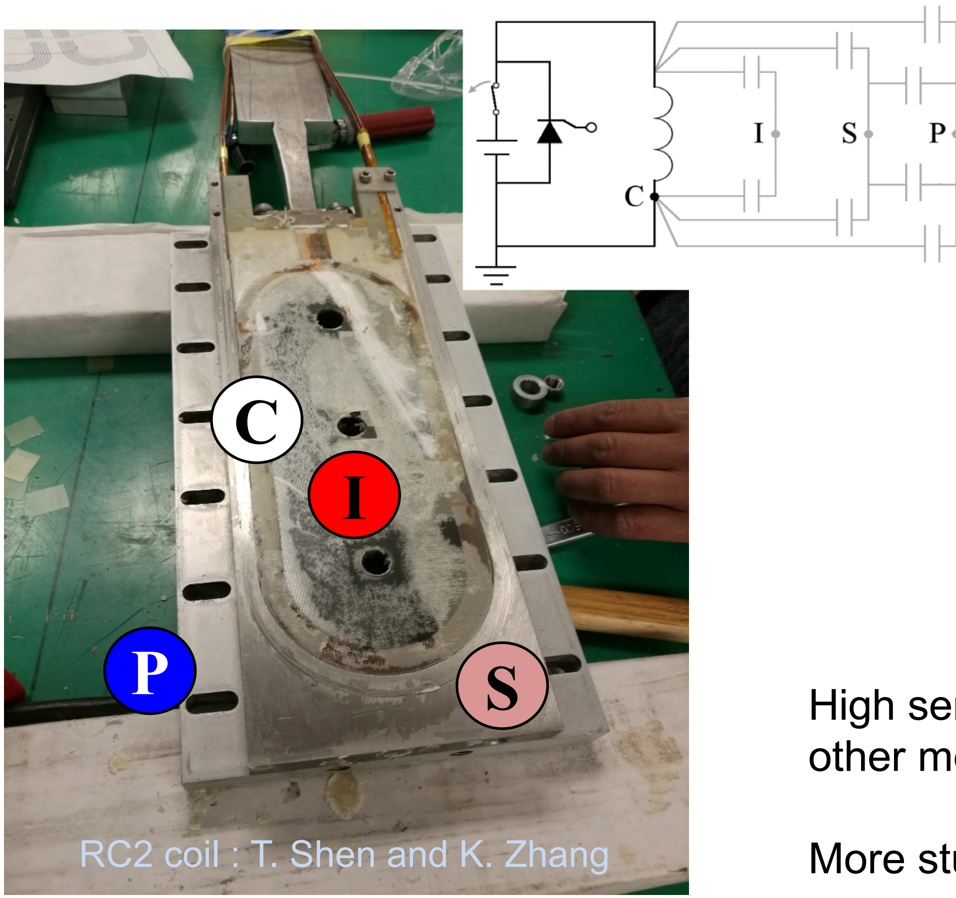
The acoustic time shift signal rises above background noise level at I=537 A which corresponds to the coil voltage of 0.3 mV and power dissipation of 0.16 W in the cable.

Capacitance Probes

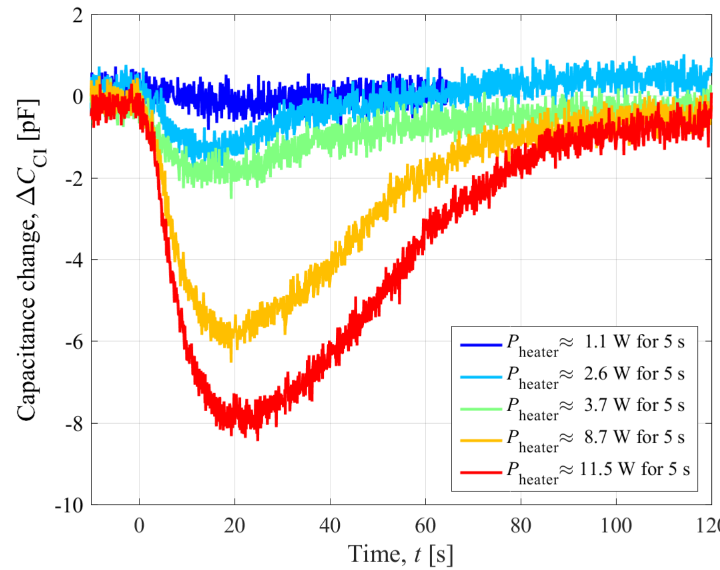
- Stray capacitance can be measured between any metallic component electrically insulated from the others. $C = \varepsilon (A/d)$ a flat plate
- Monitor capacitance to detect a quench
  - Temperature dependence of the permittivity (ε).
  - Thermal expansion
  - Mechanical movement
  - Boiling of cryogens (fluid impregnating the insulation)
- Easy to implement, non-intrusive, robust
- Sensitivity to 10 mW
- Joule heating loss – early detection of quench driven by local heating

"Quench Detection Utilizing Stray Capacitances", E. Ravaioli, M. Marchevsky, G. Sabbi, T. Shen and K. Zhang,, IEEE Trans. Appl. Supercond., v. 28, Issue 4, (2018), doi: 10.1109/TASC.2018.2812909

Principle has been demonstrated



Base capacitance C_{CI} = 2.130 nF



High sensitivity may result in false positives due to other mechanisms that could change capacitance.

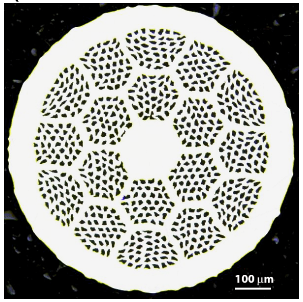
More study under controlled conditions needed

Bi-2212

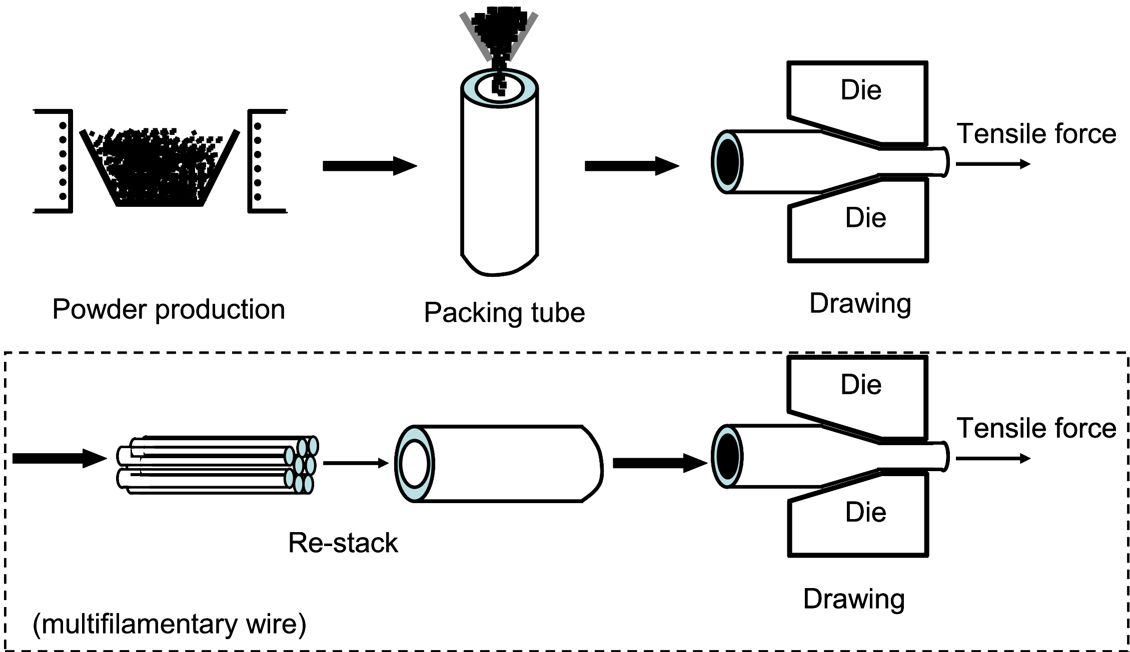
Bi-2212 Manufacture and Processing

- Fabrication via Power in Tube (PIT) in the same facilities as Nb-Ti and Nb_3Sn.
- A variety of sub-element architectures with twisted filaments as small as 15 microns.
- Improved powders lead directly to improved strand performance.
- Strand, cable or coil reacted in oxygen at 890 ^{0}C. Over-pressure processing at 50 – 100 bar significantly improves performance.
- Strain sensitivity due to low modulus of silver (~70 MPa)

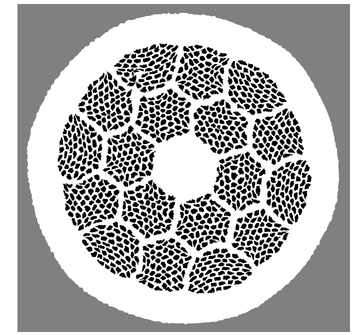
(2212 RW, OI-OST, now Bruker OST)



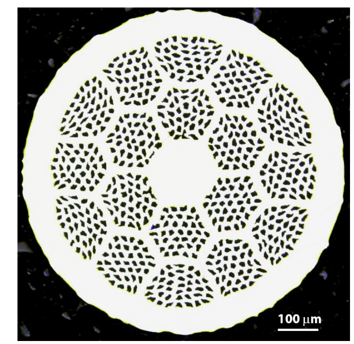
Bi-2212 Manufacture and Processing



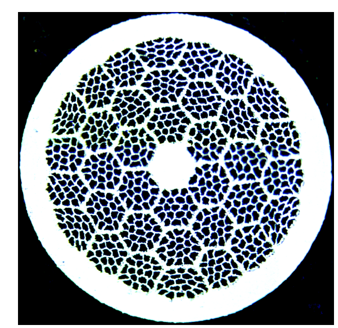
55x18

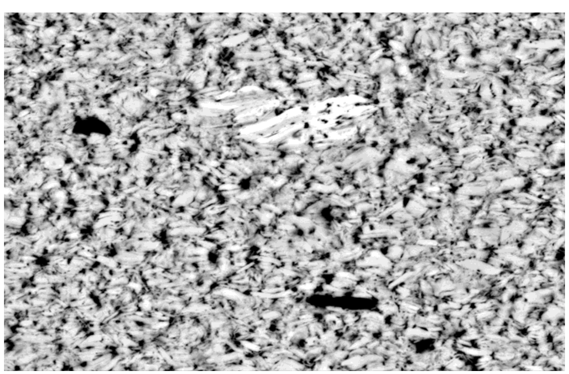


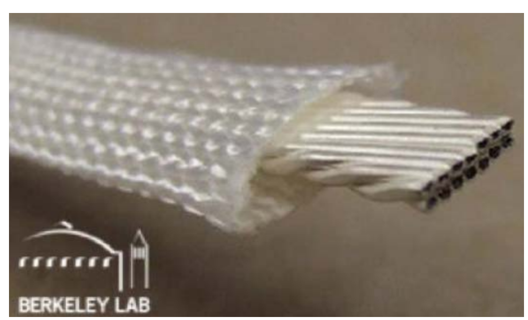
36x18



19x36

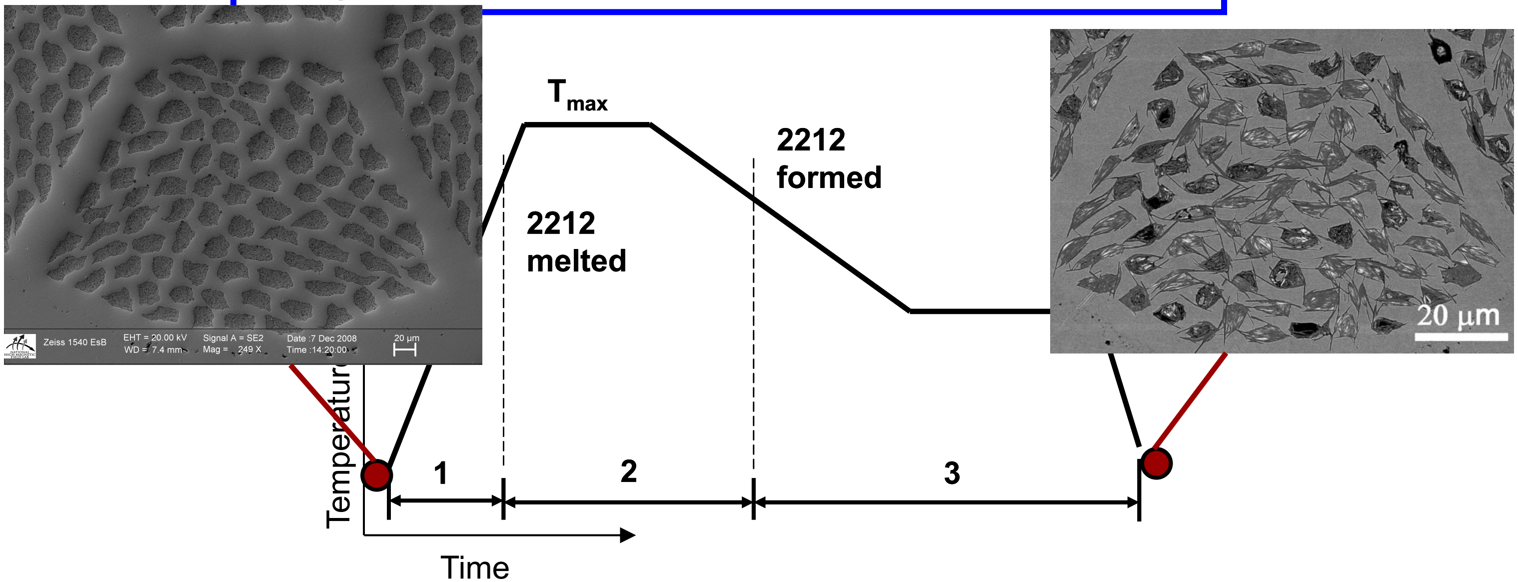






PIT 2212 is transformed to a high J_c conductor using a partial melt processing

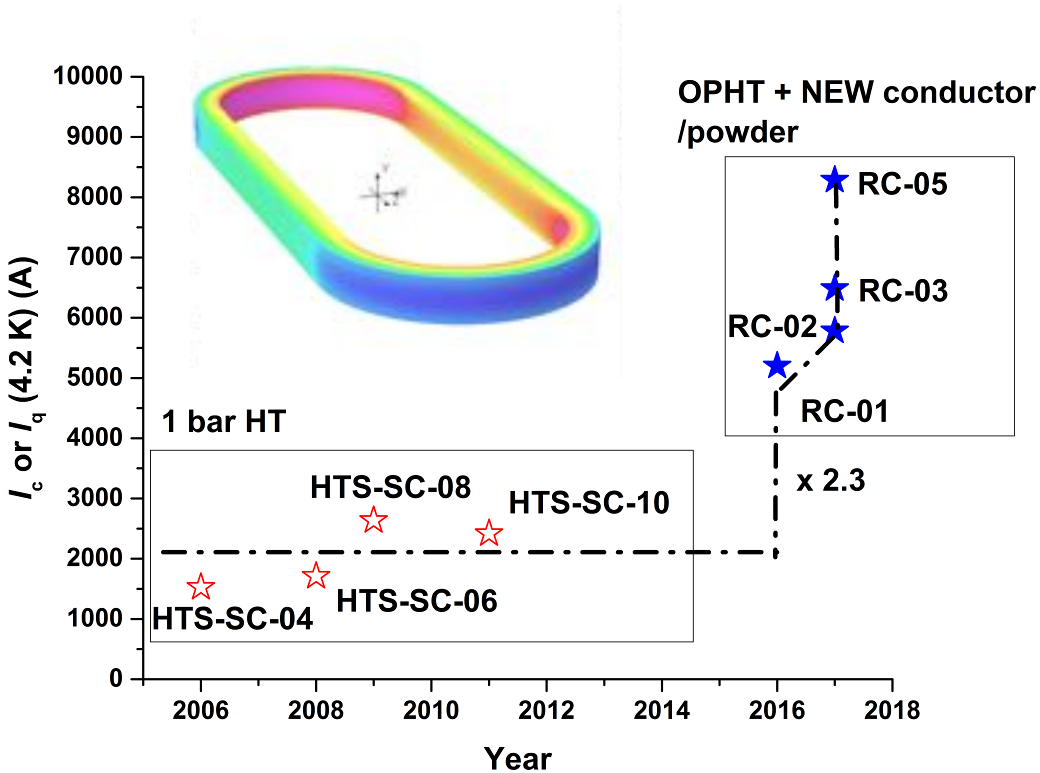
Microstructures of fully reacted wires are complicated.

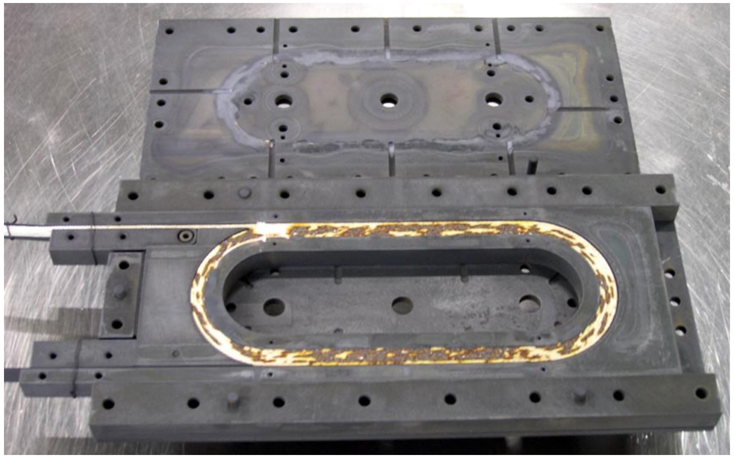


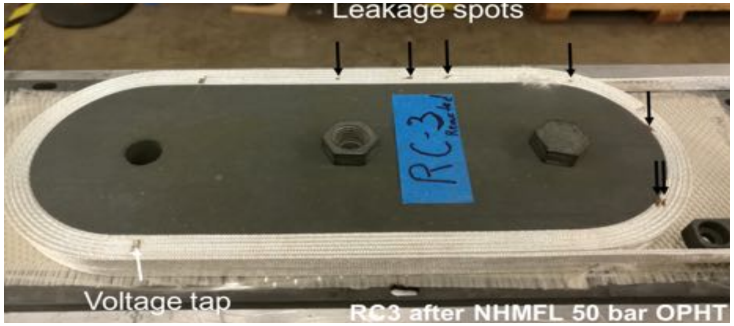
2212 → Liquid + solid phases → 2212

a peritectic reaction

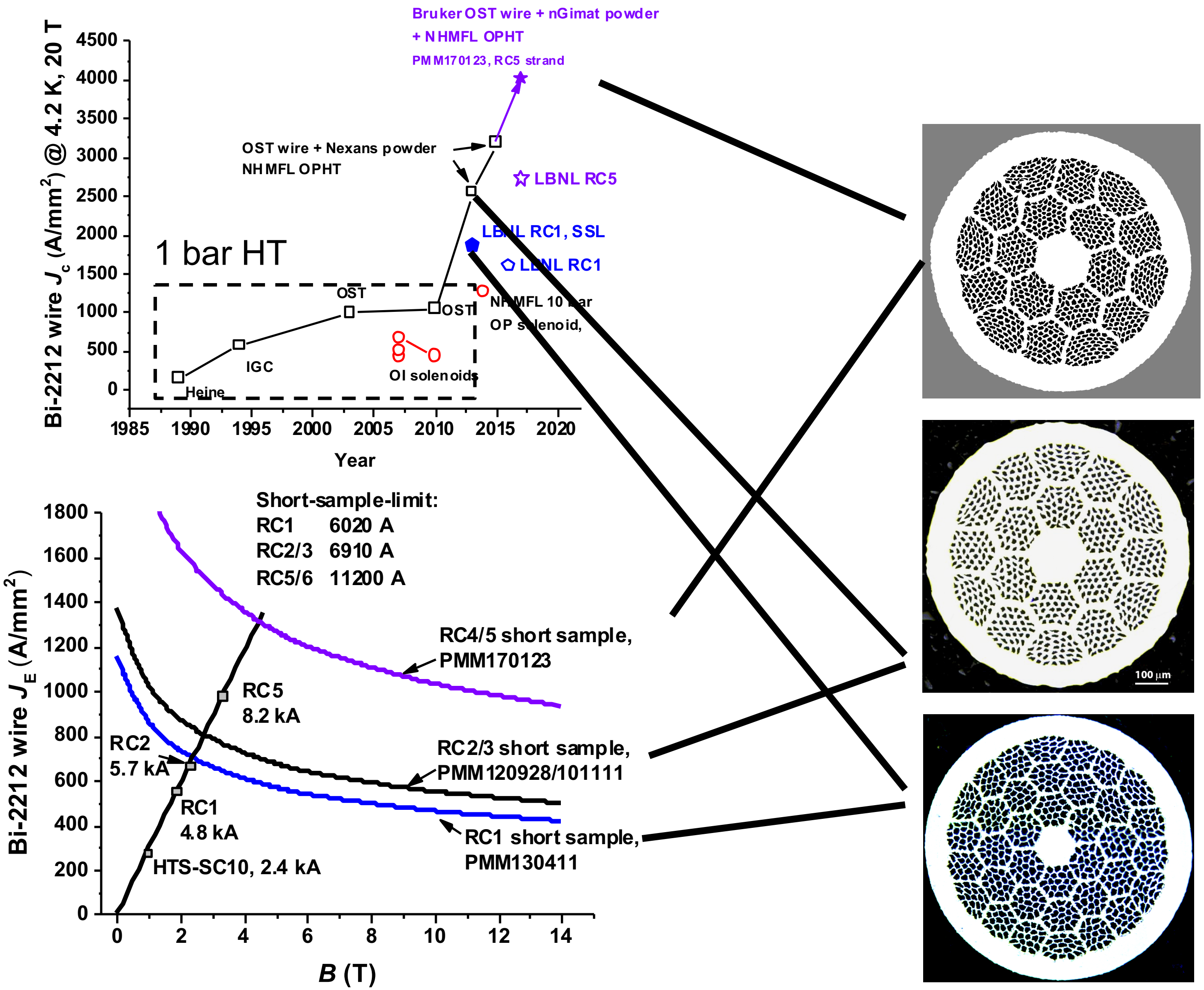
- Early coils exhibited extensive leakage
- Fairly recent discovery that bursting was caused by bubble formation (and chemical incompatibility)







Significant J_c Improvement with Over Pressure Heat Treatment (OPHT)



PMM170123, 55x18, nGimat powder LXB-52

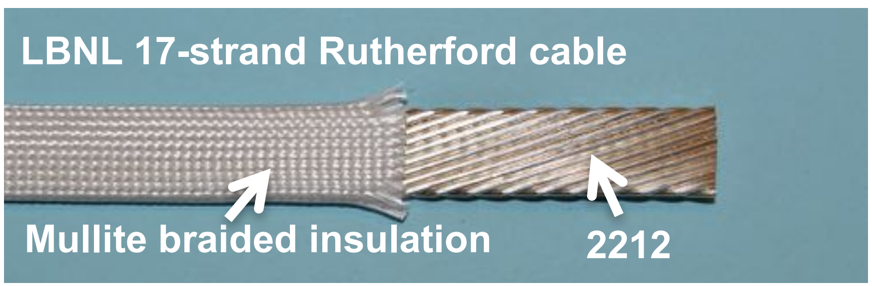
Conservative short sample J_E used.
See Larbalestier, MT25 talk

PMM101111, 36x18, Nexans powder 77

PMM130411, 19x36, Nexans powder 77

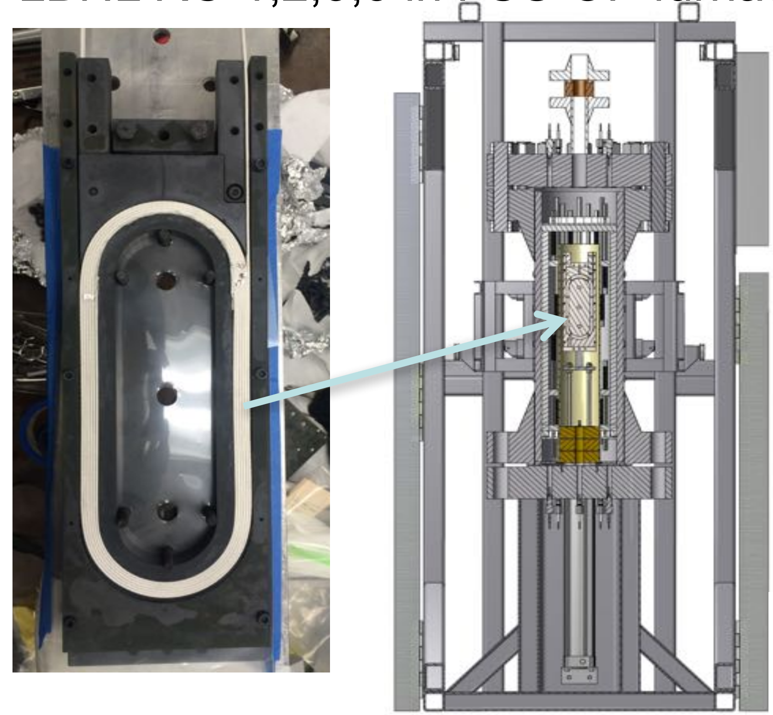
Reaction Process – Getting J_c

- Round strands are made into Rutherford cable or variants
- Too brittle for react and wind process – start with a coil
- Insulation, mandrel, reaction fixtures must withstand 890^0C +/- 5^0C in O_2 atmosphere

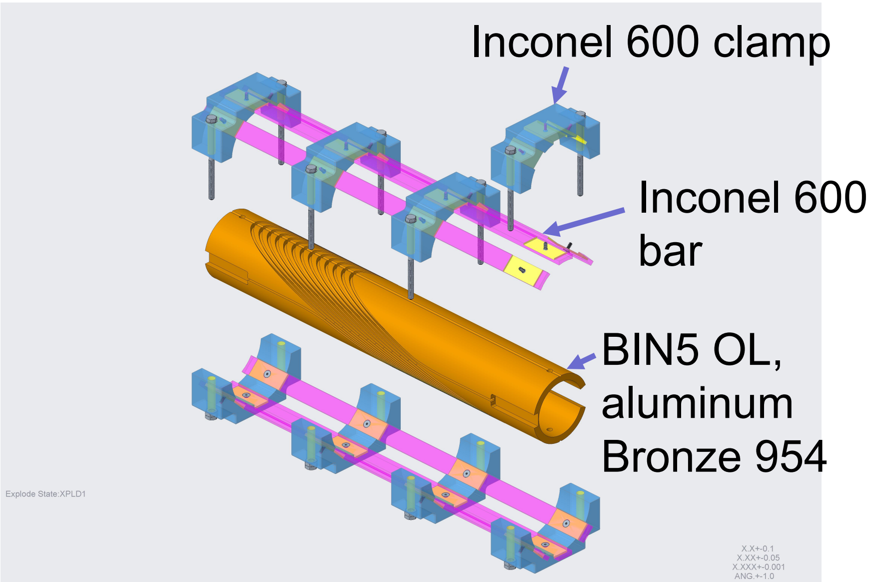


Most recent insulation scheme is TiO_2 slurry (Chemically benign) + mullite sleeve

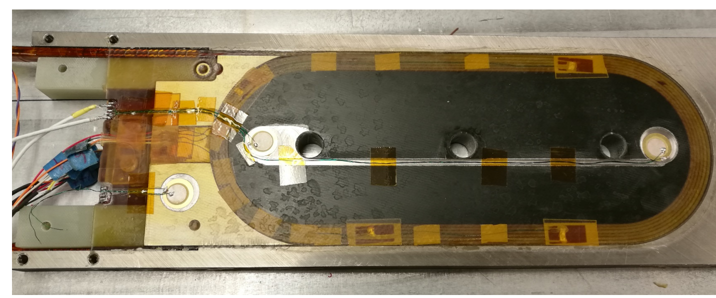
LBNL RC-1,2,3,5 in FSU OP furnace

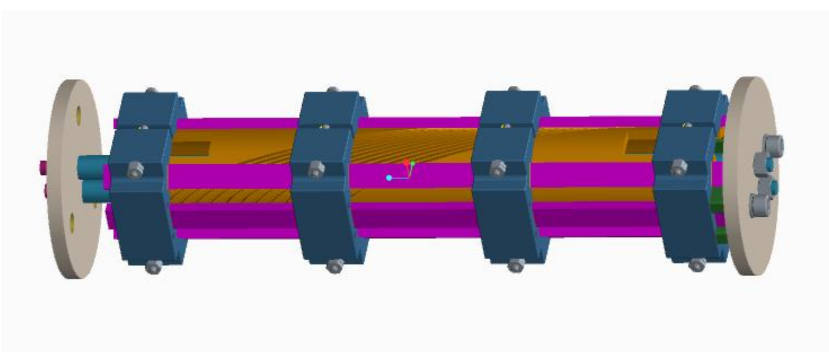


Reaction and Post-Reaction Fabrication Steps



- Post Reaction Steps same as for Nb_3Sn
  - Lead splices
  - Voltage taps
  - Impregnation
  - Assembly into support structure





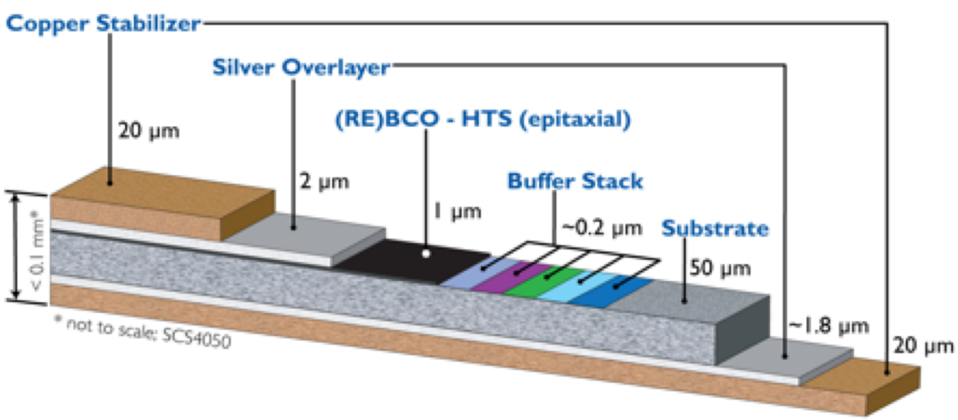
ReBCO

ReBCO Manufacturing and Processing

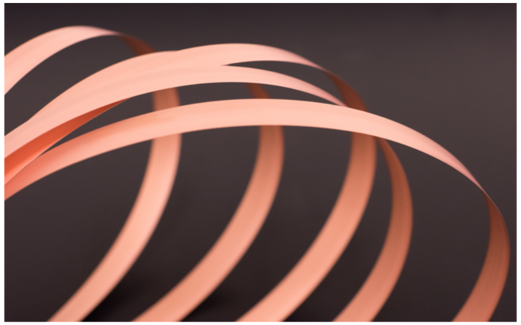
- Rare-earth (Yttrium etc.) barium copper oxide (ReBCO), is a crystalline chemical compound.
- Only available in tape form (limits options for use).
- In most cases the fabrication of this material involves the deposition of a thin layer of YBCO on a flexible substrate coated with one or more buffering metal oxides encased in copper (known as coated conductor).
- There are now two commonly used processes, Rolling Assisted Biaxially Textured Substrates (RABITs) and Ion-Beam-Assisted Deposition (IBAD). For mechanical reasons, the IBAD method is more widely selected by suppliers, e.g. SuperPower , Bruker and Theva.

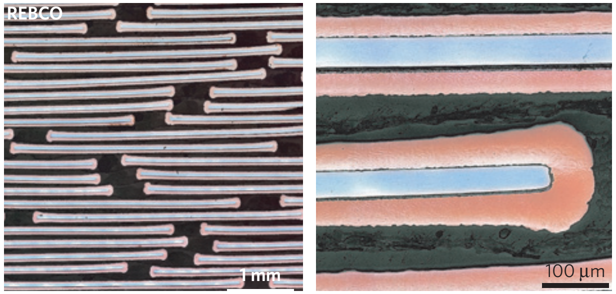
ReBCO Manufacturing and Processing

- Multiple producers in the US, China, Japan, Korea, Russia and the EU
  - Many with Hastelloy substrate with a yield strength of 1 Gpa
- Performance goals
  - Increase superconducting layer and reduce substrate thickness (higher J_e)



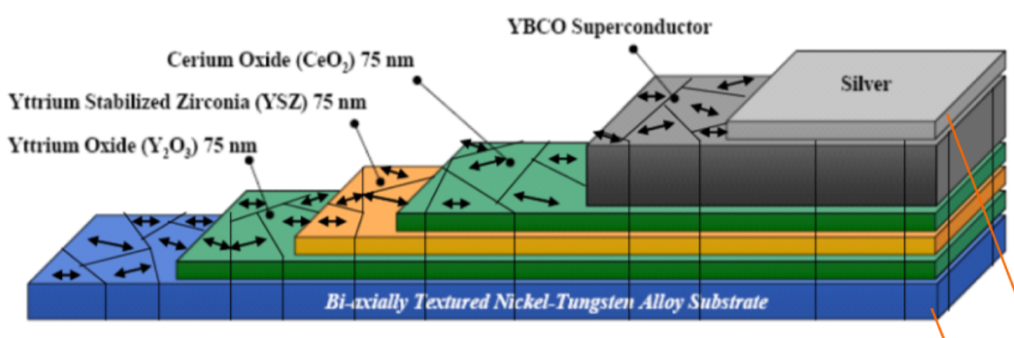
(REBCO CC, Courtesy of Superpower)

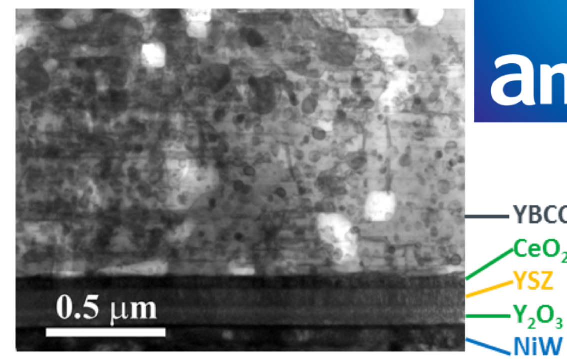




Amperium™ (2G) Wire Architecture

Layer-by-Layer Deposition of a Bi-axially Textured, Multi-layer Composite



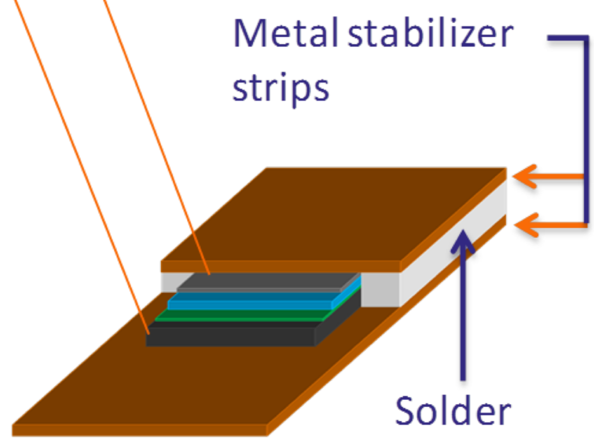


Ag coat
- DC sputtering

YBCO:
- MOD of TFA-based precursor with RE-based nanoparticles

Buffer Stack:
Y_2O_3 – YSZ – CeO_2
- High rate reactive sputtering

Substrate:
Ni-5a%W Alloy
- Deformation texturing

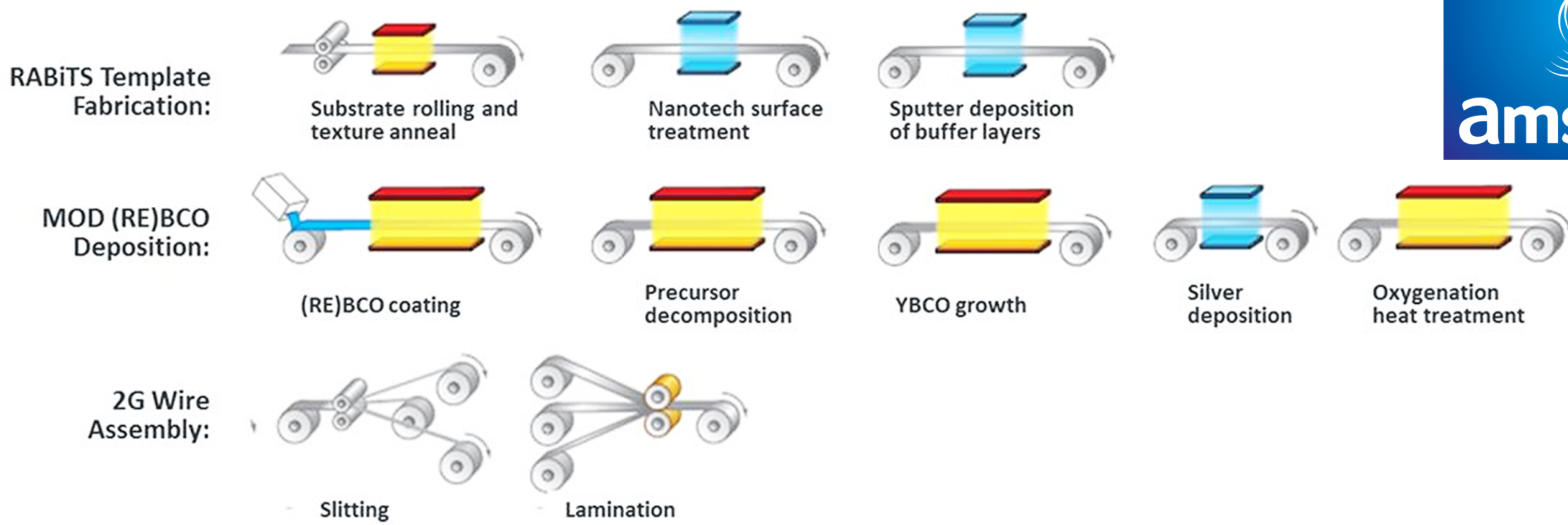


Laminated Wire

Lamination of composite strip allows customization of mechanical and electrical properties

Courtesy Marty Rupich, American Superconductor

AMSC HTS Wire Manufacturing Process



Advantages

- Wide-web processing (low cost)
- High rate, inexpensive materials, high material utilization
- Highly reproducible process (strip-to-strip and within strip)
- Robust, high strength wire architecture
- Customizable wire architecture

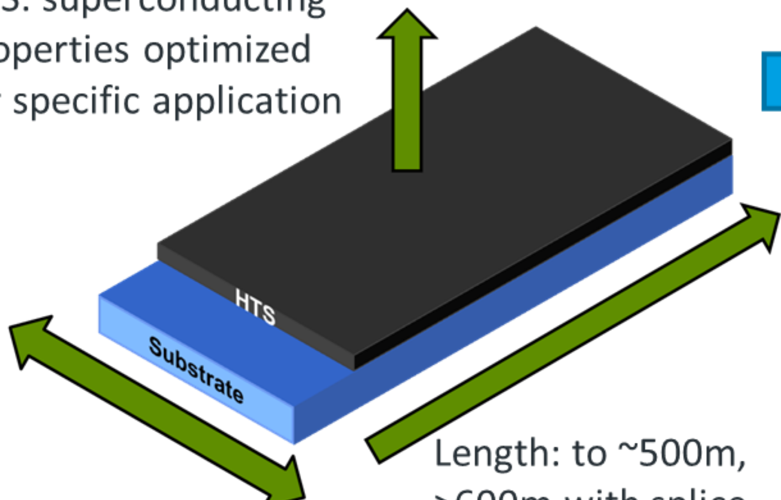
Courtesy Marty Rupich, American Superconductor

Flexibility in SC, electrical, mechanical and dimensional properties

Courtesy Marty Rupich, American Superconductor

HTS Strip: Scalable in 3 Dimensions

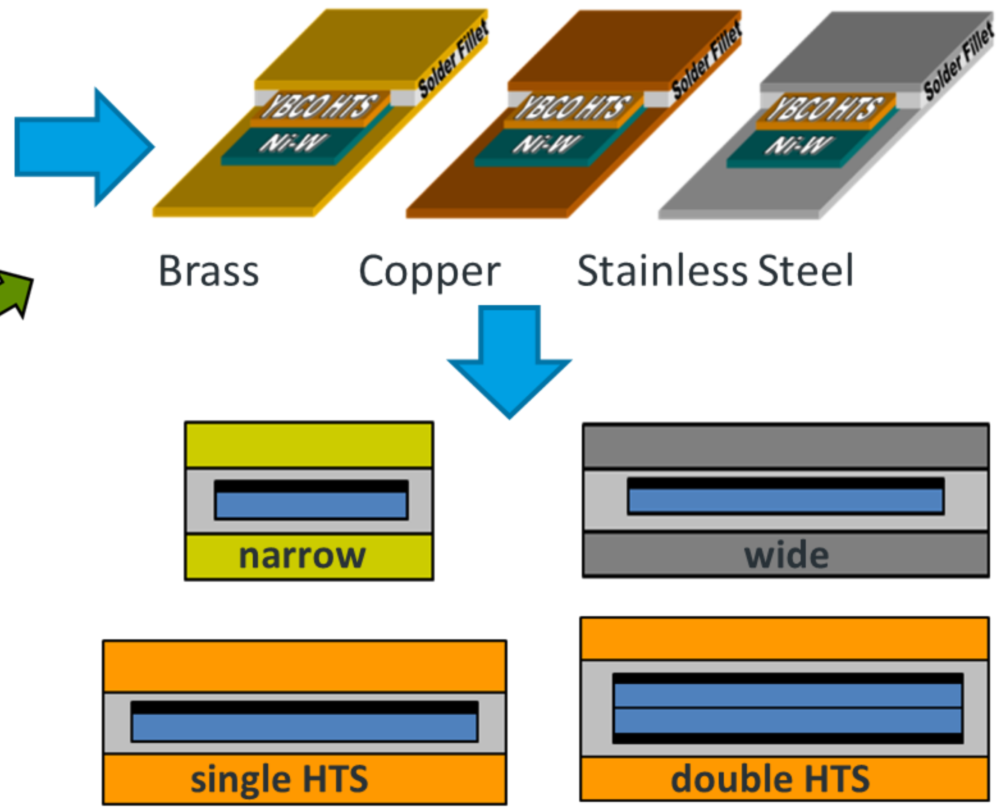
HTS: superconducting properties optimized for specific application



Length: to ~500m, >600m with splice

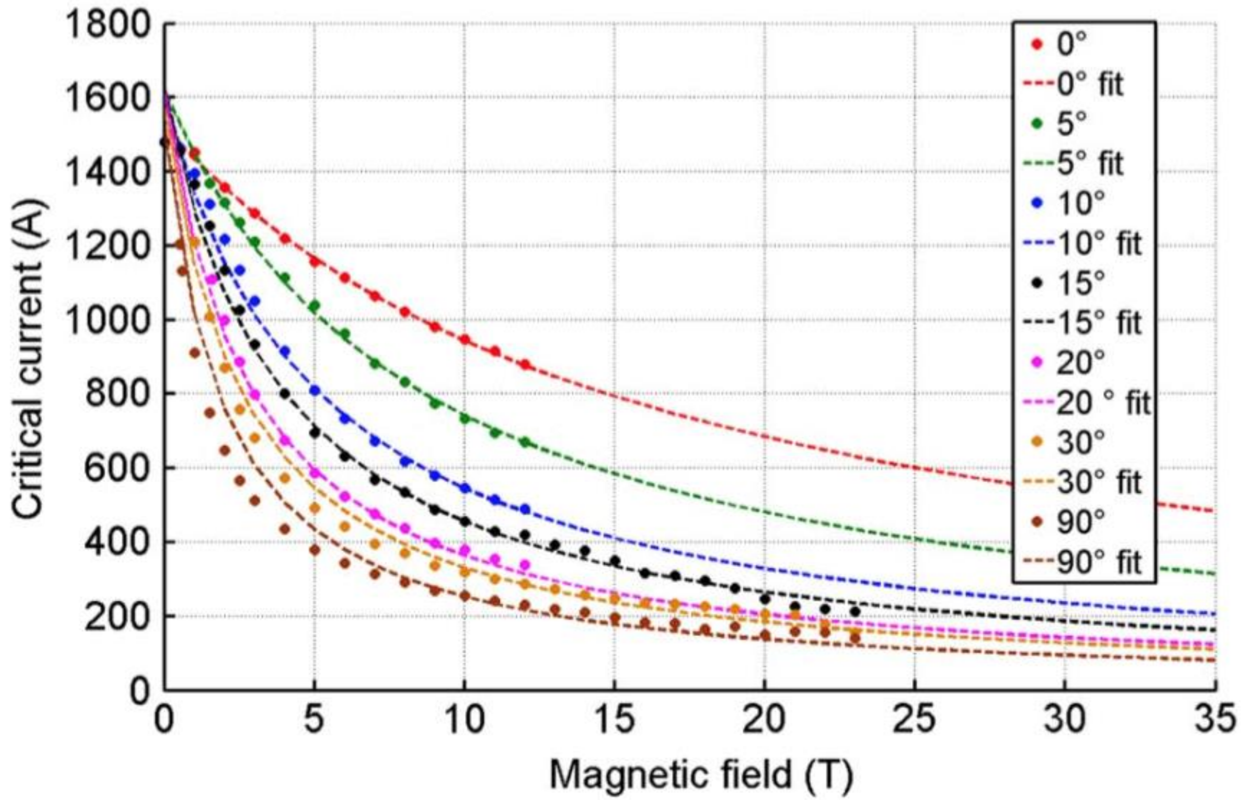
Width: precision slit to product width from wide web

Customized Laminated Wire



Transverse Cross-section

ReBCO Anisotropy



Anisotropic dependency of 4 mm wide SuperOX ReBCO tape

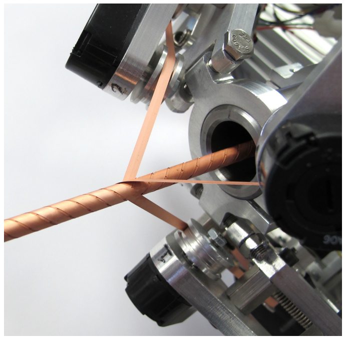
T. Benkel et al, 2016, REBCO Performance at High Field With Low Incident Angle and Preliminary Tests for a 10-T Insert, IEEE Trans. Appl. Supercond. Vol. 26, No. 3, 4302705

ReBCO Technological Challenges

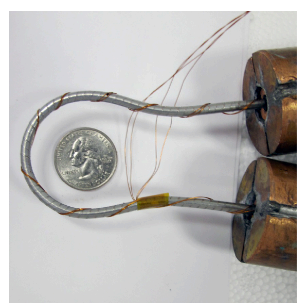
- High current cables
  - A few choices but none are ideal
    - Conductor on Round Core (CORC®)
    - Stacked tapes
    - Roebel
  - Joints
  - Current Sharing
- Quench Detection and Magnet Protection
- Impregnation
  - Delamination of tapes
- Magnetization (Field Quality)
  - Striation
- Anisotropy
  - Coil geometries

ReBCO Cables

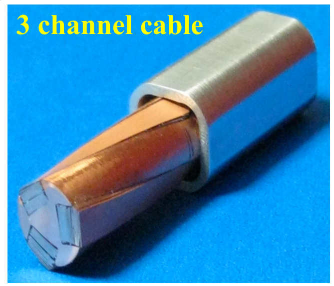
ACT CORC®



D C van der Laan et al.,
SuST, 24, 042001, 2011

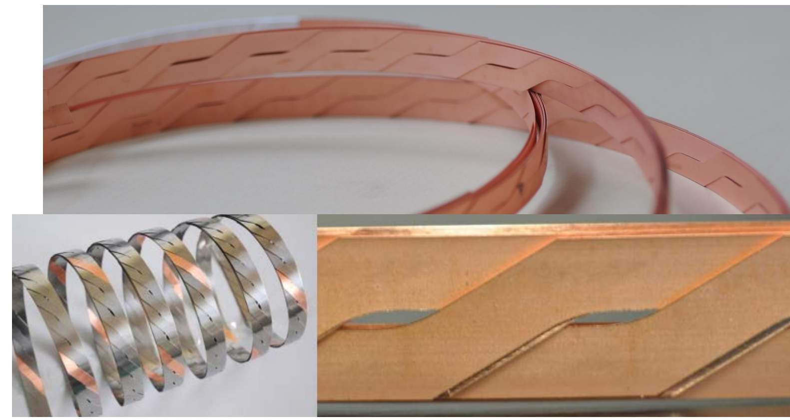


MIT Twisted Stacked-Tape Cable



M. Takayasu et al.,
SuST, 25 (2012) 014011

KIT Roebel cable



A. Kario et al.,
SuST, 2013, 26 085019

Goals:

- High current
- Transposed conductors
- Current sharing
- Windability

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CORC® wires (2.5-4.5 mm diameter)

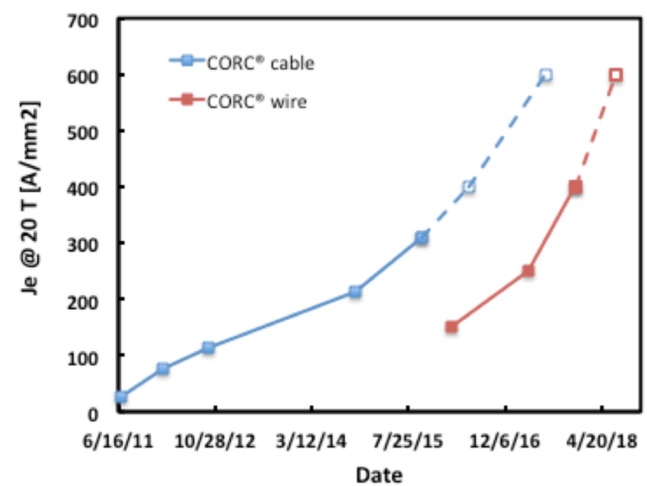
- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter

Closing in on J_e > 600 A/mm² goal

- J_e (20 T) now exceeded 400 A/mm² in CORC® wire
- Combined with I_{opp}(20 T) > 6,500 A
- Next step is thinner substrates (20 – 25 μm)

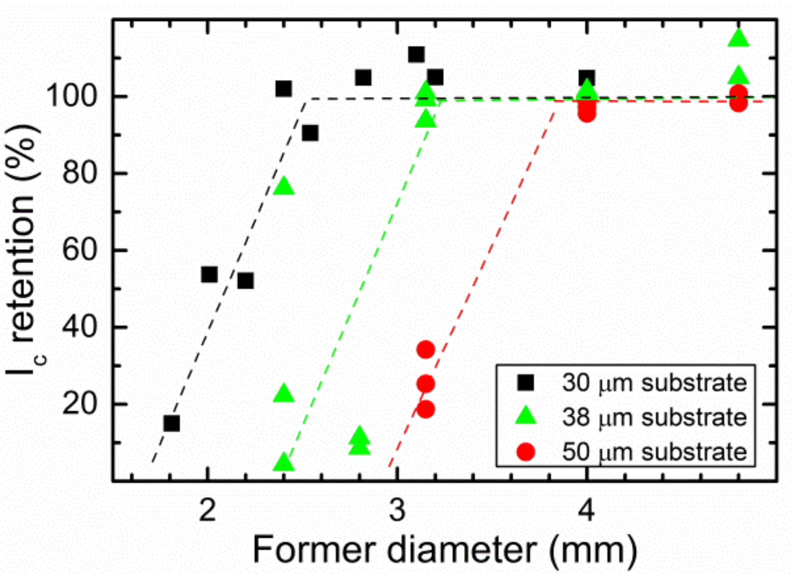


CORC® Development Goals

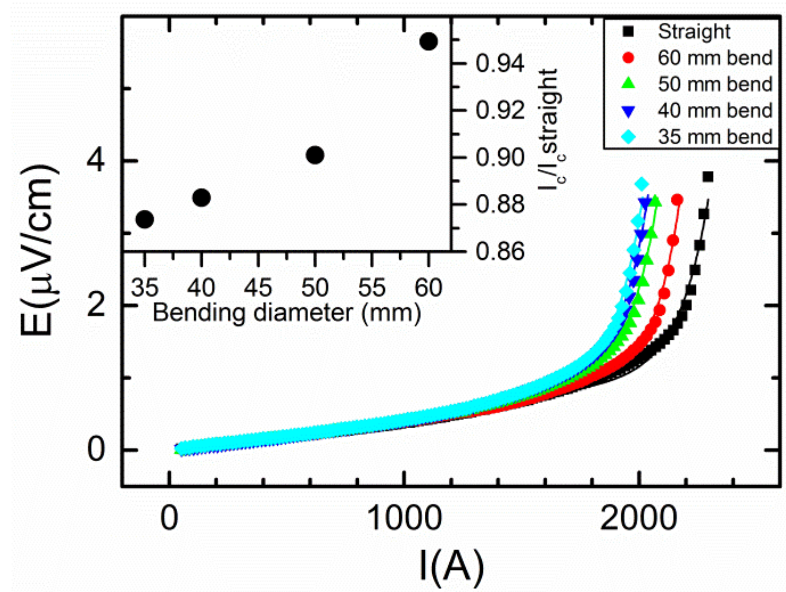
- Increase current density by pushing tape development
  - Higher J_c
  - Introduction and control of artificial pinning centers
  - Thicker SC layer (though that may have some negative effect on minimum bending radius of the tape)
- Keep the J_c (higher J_e)
  - Thinner substrates
  - More layers increase J_e toward tape limit
- Improve cable flexibility
  - Goal is to maintain flexibility for higher tape-counts
  - Thinner substrates
  - Smaller tape widths
- Compact, low resistance joints and leads
- Understand mechanical limits

Small bending diameters a plus for accelerator magnets

- Minimum bending diameter depends on thickness of tape substrate



Recent test result on 29-tape CORC® wire



Decreasing tape width will also improve flexibility

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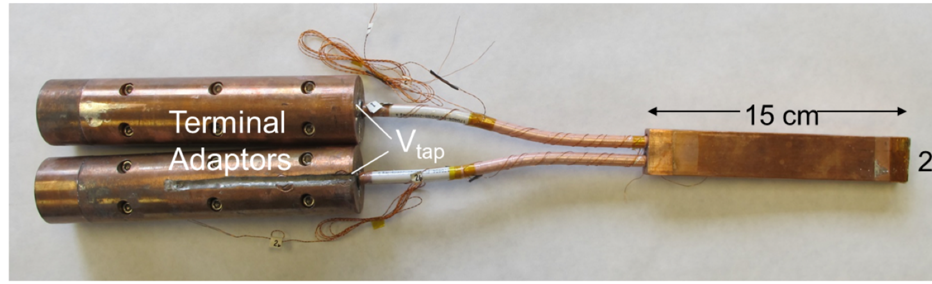
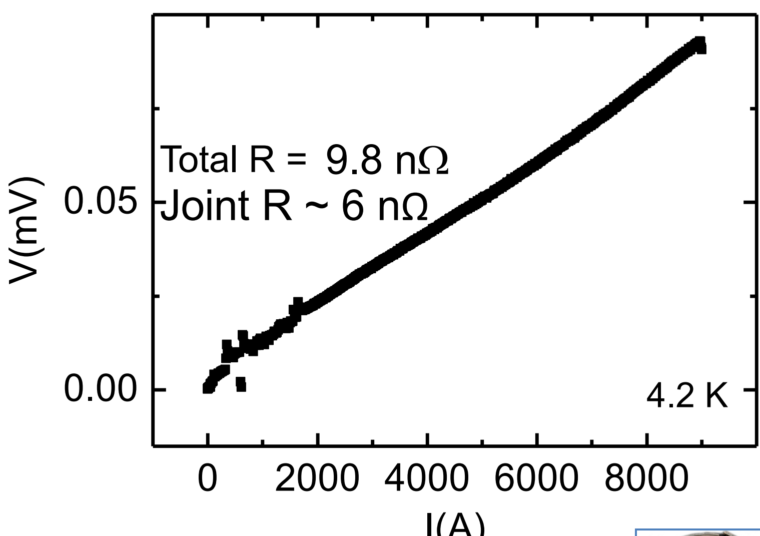
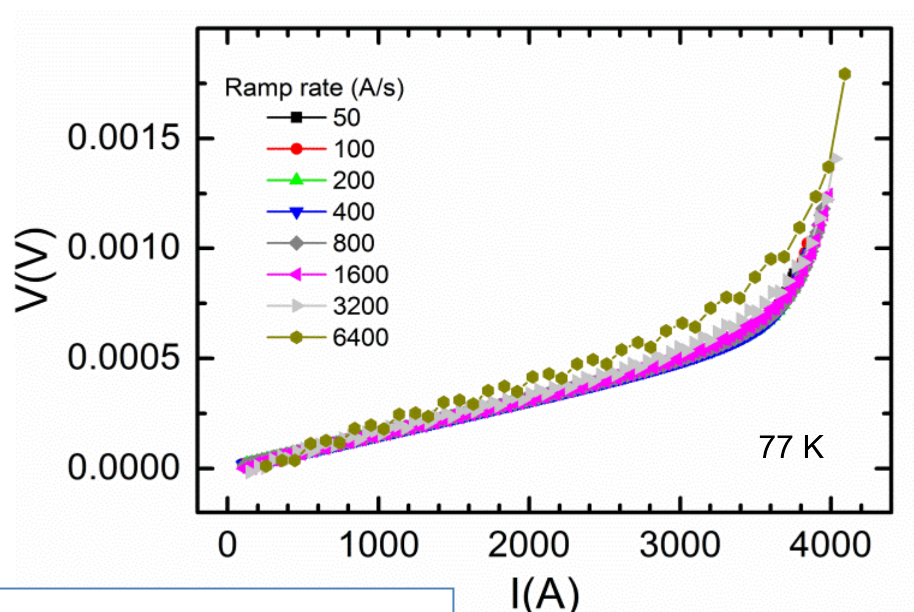
Indium joint

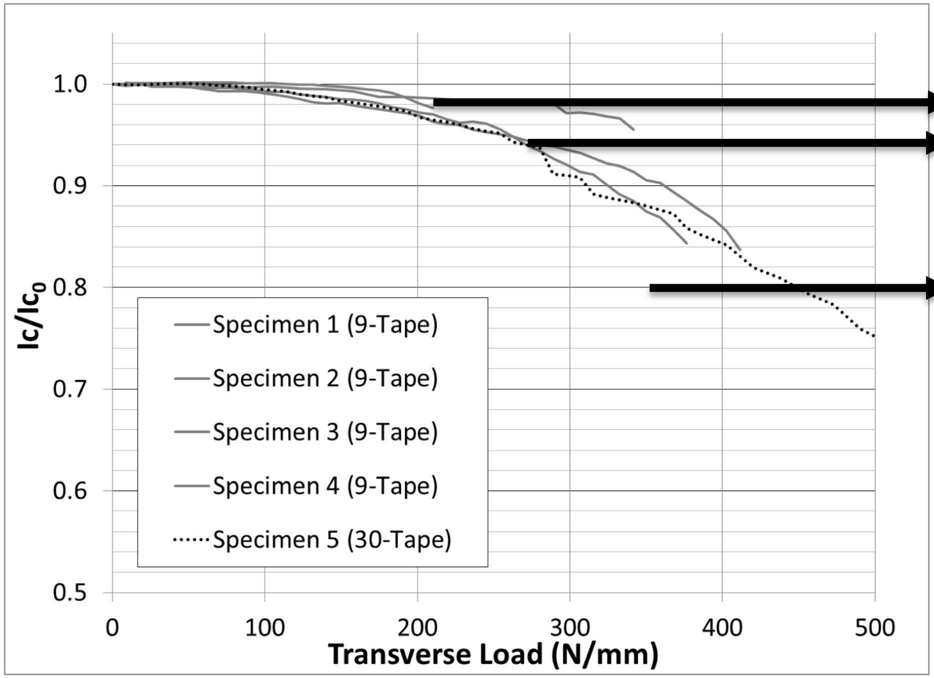
Voltage across terminals includes contact resistance of terminals in addition to joints



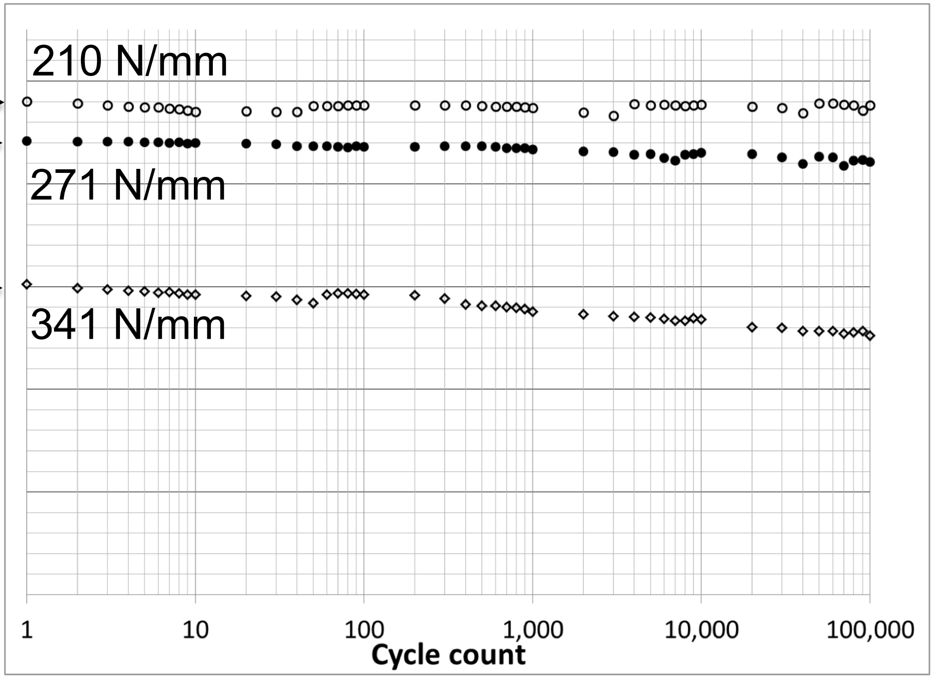




Compressive Load



Cyclic Loading



Courtesy Dustin McRae and Jeremy Weiss

T = 76K

CORC® Electromechanical Testing
A Brief Overview

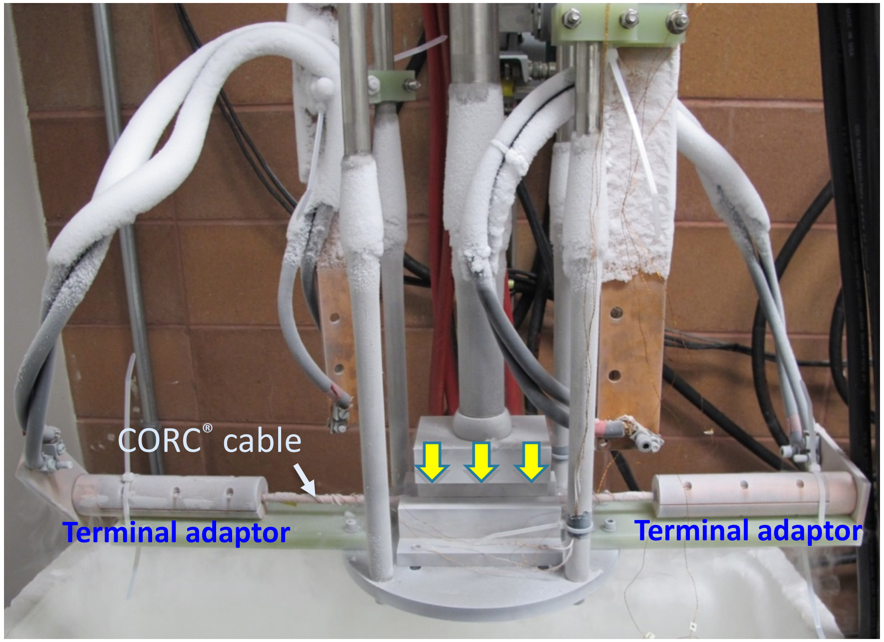
Following slides provided by

Dustin McRae, Danko van der Laan & Jeremy Weiss
Advanced Conductor Technologies & University of Colorado

5/25/2018

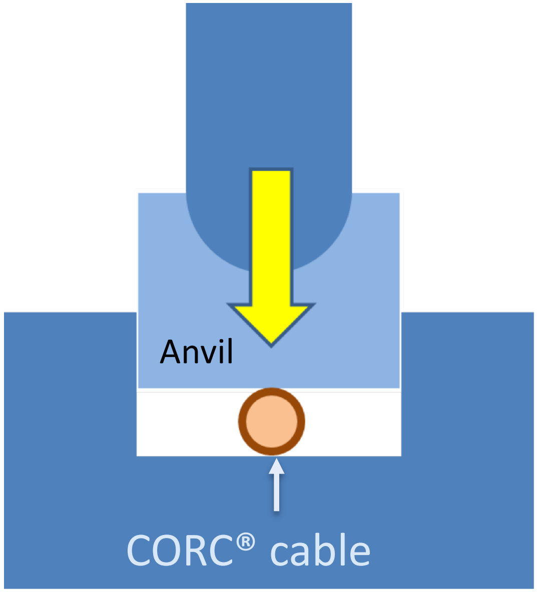
Transverse Compressive Test Equipment

MTS test setup, loading up to 10,000 Lbs (44 kN)



Side view

Load applied results in a line-contact against the conductor



Sample Description

CORC® wire 1

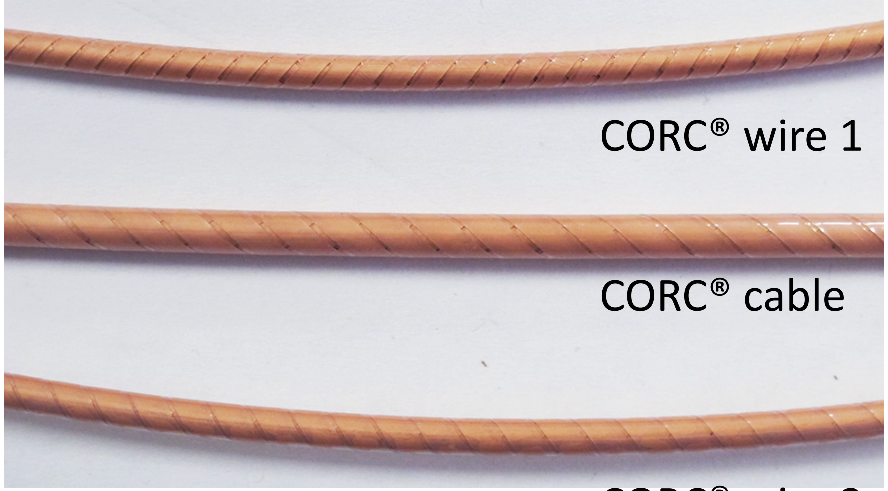
- 11 layers, 27 tapes total
- 2 mm wide tapes
- Gap spacing 0.3 - 0.4 mm
- 30 μm thick substrate
- 2.55 mm thick former
- REBCO winding strain: -1.16 %

CORC® wire 2

- 6 layers, 12 tapes total
- 3 mm wide tapes
- Gap spacing 0.4 mm
- 30 μm thick substrate
- 3.20 mm thick former
- REBCO winding strain: -0.93 %

CORC® cables

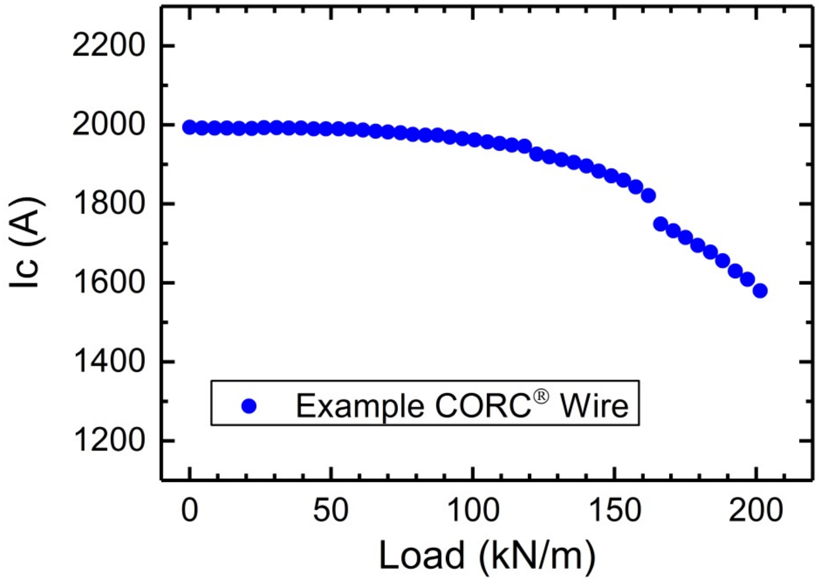
- 3 layers, 9 tapes total
- 4 mm wide tapes
- Gap spacing 0.1 mm or 0.5 mm
- 50 μm thick substrate
- 4.92 mm thick former
- REBCO winding strain: -1.00 %



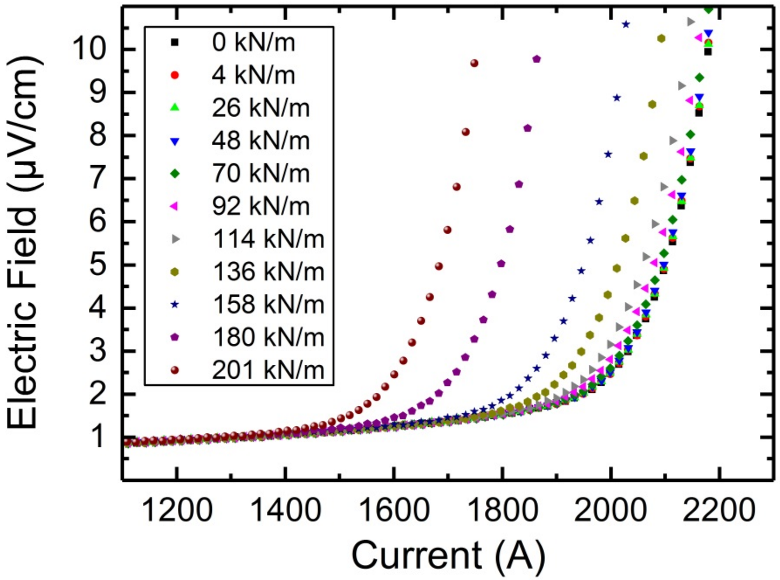
Monotonic loading procedure

1. Performed incrementally in load control
   => Accounts for continuously-changing state of thermal contraction in load fixture
2. Hold load constant, run I_c test, load to next load increment
3. Repeat

Typical Ic vs Load graph



V-I curves at several loads

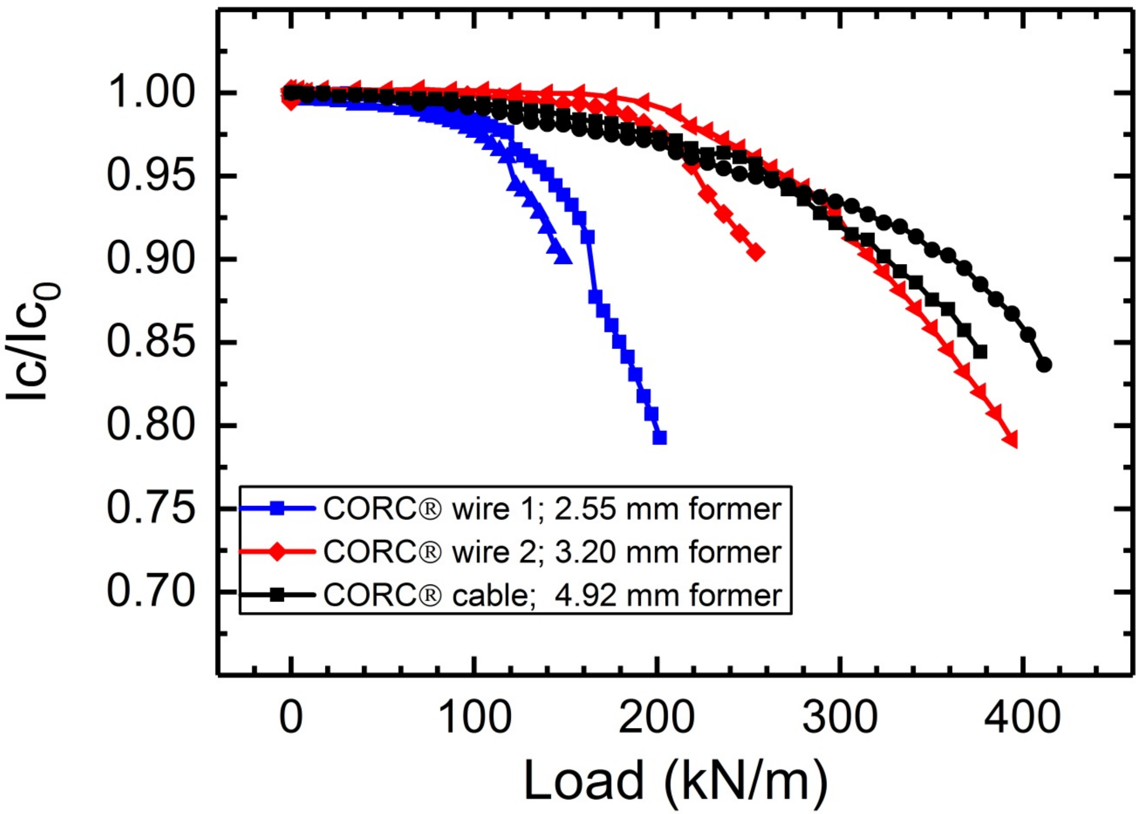


Monotonic Transverse Compression Data

Some trends can be seen

•CORC® wires with smallest former, and REBCO layer close to -1.25 % critical strain are most sensitive to transverse compression

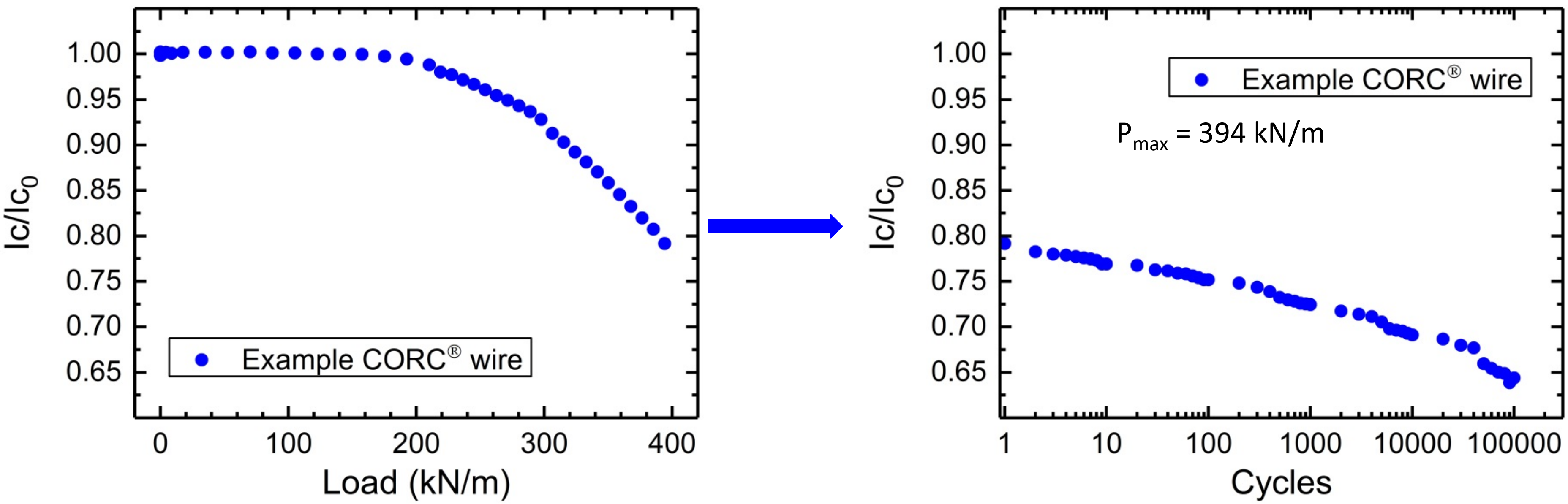
•CORC® wires and cables with comparable REBCO strain show similar load dependence



Fatigue Test Procedure

Preliminary fatigue test procedure

- Monotonic loading of virgin sample to pre-selected I_c degradation load (for instance $I_c/I_{c0} = 0.8$)
- Fatigue cycling at stress amplitude ratio $P_{min}/P_{max} = 0.1$
- I_c was measured at peak load up to 100,000 cycles



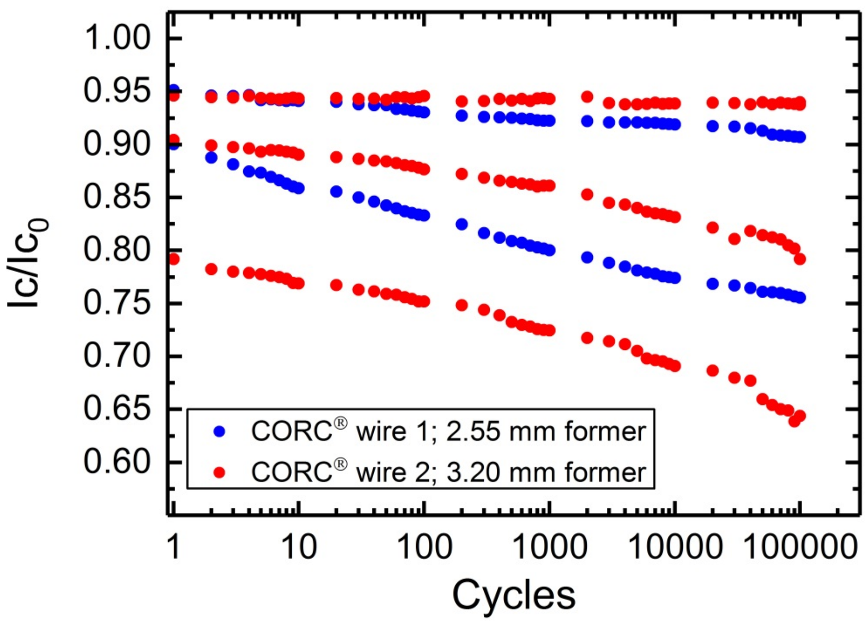
Fatigue Data under Transverse Compression

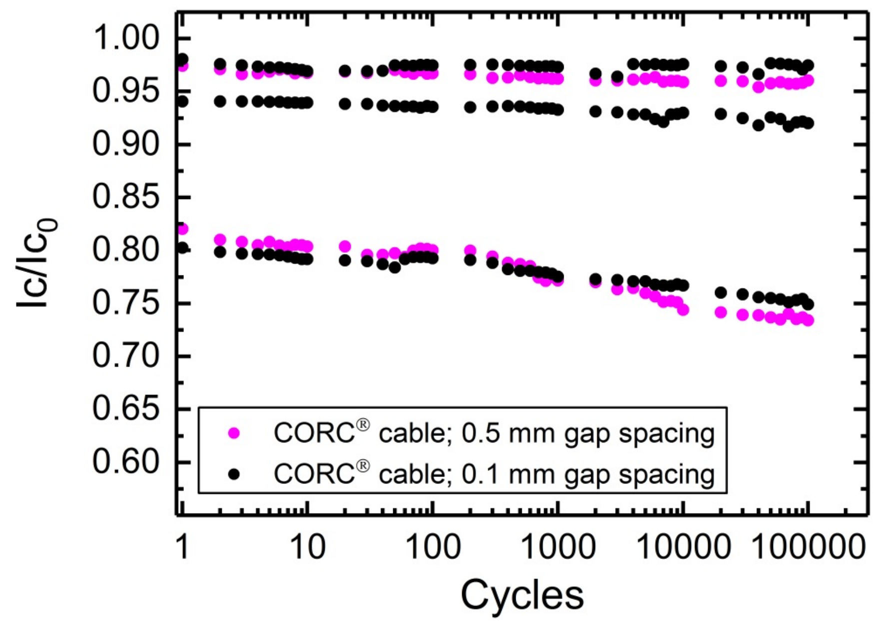
Overall promising for safe operation in magnet applications

- I_c does not drop off a cliff with cycle count at a constant load amplitude
- Degrades gradually and predictably, usually only after significant initial degradation

Some trends can be seen

- REBCO winding strain, which depends on former size and tape substrate thickness, has significant impact on fatigue degradation
- Gap spacing has small effect on fatigue degradation





Preliminary Conclusion

Although tests are ongoing and different sample configurations are being tested as we speak

•The resilience of CORC® cables and wires to transverse compression up to 100,000 cycles is very promising

•The I_c retention after 100,000 cycles is especially high when the peak load didn't degrade Ic by more than 5 – 10 % before cycling

•Magnets will likely be designed at transverse loads resulting in no more than 3 – 5 % I_c degradation, which means that load cycling likely won't have a significant impact on the magnet performance

Next step: axial tension

Roebel

- A design for low loss copper cables in 1914 by Ludwig Roebel. First HTS Roebel cable made by Karlsruhe Institute of Technology (KIT)
- Pros
  - Multi-strand cable – higher current
  - Relatively good J_e – compact windings
  - Provide full transposition of the strands along the cable direction.
- Cons
  - Throw away half the conductor!
  - Finite tolerances generate transposition errors that limit length (some ideas for monitoring and compensating)
  - Long transposition length
  - Edge damage – delamination, reduced J_e
  - Still a tape with respect to windability
  - Non-uniform stress transvers stress distribution

Twisted-Stacked Tape Cable (TSTC)

Stacked-Tape Twist-Winding

Simple, compact – high J_e
Large bend radii – e.g. 6% degradation for radius of 14 mm
Easy scale-up
Long pitch length
Partial tansposition

Twisted stacked cable composing 32 YBCO tape (left) and the flared- end coil with a sharp bending (right).

M. Takayasu, 2013, Conductor Characterization of YBCO Twisted Stacked-Tape Cable, IEEE Trans. Appl. Supercond. Vol. 23, No. 3, 4800104

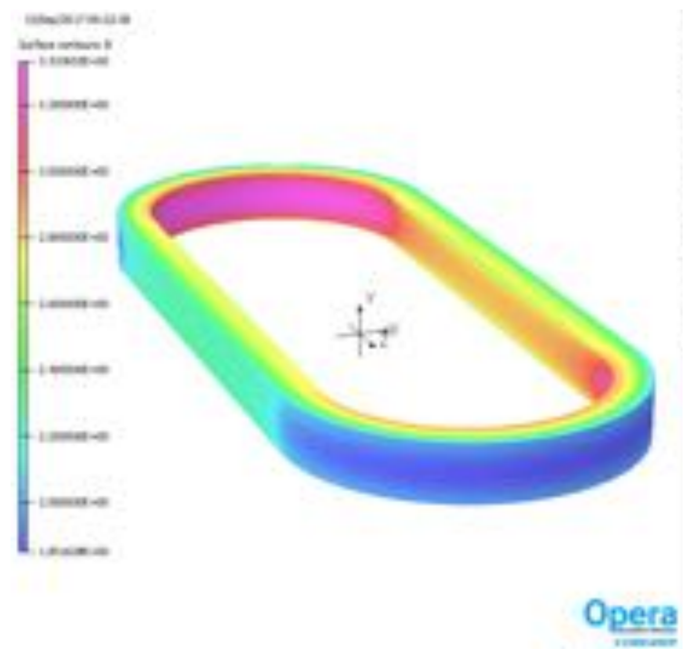
Selected Examples from Current Programs

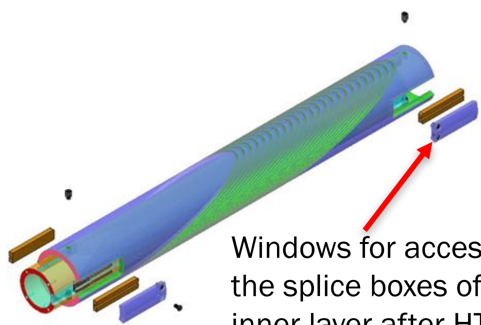
US Magnet Development Program
Bi-2212

- Focus is on accelerator-relevant geometries (dipoles, … quads)
  - Starting with small racetrack coils and CCT
  - Develop basic technology
  - Fabrication techniques
  - Feedback to materials developers

T. Shen, Program Lead, and
L. Garcia Fajardo, LBNL

RC5 – peak field – 3.33 T





Windows for accessing the splice boxes of the inner layer after HT

<u>Specific goals of BIN4</u>:

- Test I_c when undergoing 1 bar HT
- Investigate conductor quality after heat treating **both layers together**
- Reach 0.7 T in the bore

<u>Specific goals of BIN5</u>:

- Test I_c when undergoing 50 bar HT

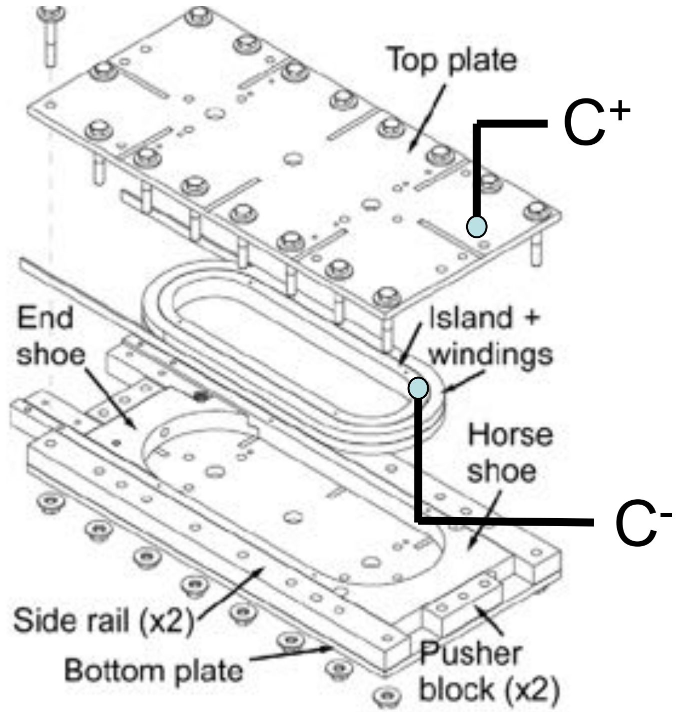
<u>Goals of BIN4 and BIN5</u>:

- Investigate technology issues during manufacturing process and quench propagation and protection techniques.

BIN = Bismuth INsert

Bi-2212 Racetrack Coils (RCn)

- 2-Layer/6-turn racetrack coil
- 17-strand Rutherford cable
  - 1.4mm X 7.8 mm (0.8 mm strand)
- 140 m of conductor, 8 m of cable
- 50 bar OPHT at FSU MagLab
- Various impregnation materials
  - Wax
  - NHMFL Mix 61
  - CTD 101-K



Replace with generic

Courtesy T. Shen, L. Garcia Farjado, LBNL

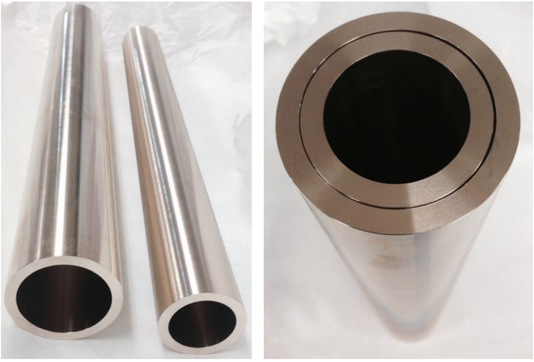
Bi-2212 Racetrack Coils (RCn)

- Summary of results (note that field is a little more than 3 T)
  - Safely protected
  - No training
  - Operated at ~ 8kA
  - $J_{e,\ cable}$ = 740 A/mm^2 (Extrapolated to 20T $J_{e,\ cable}$ = 412 A/mm^2)
  - High stability for ramped operation
  - OPHT didn't eliminate all leaks. Addition of TiO_2 slurry (Jun Lu, NHMFL)
  - Used to explore acoustic and capacitive quench detection
  - An extremely useful tool for technology development
  - Next Steps
    - 5T Common Coil configuration
    - Insert test in 14 – 15 T outsert

Courtesy T. Shen, L. Garcia Farjado, LBNL

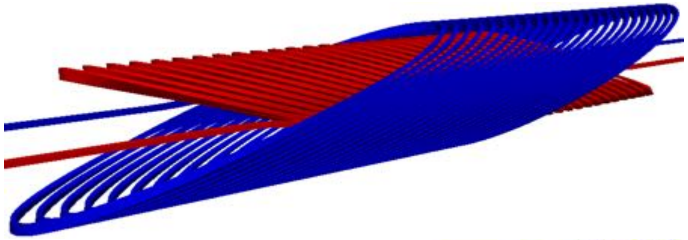
Bi-2212 CCT Insert Coils (BINn)

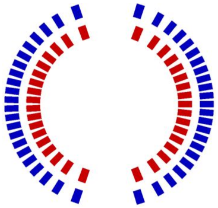
- CCT geometry is of particular interest for Bi-2212
  - Simple fabrication
  - Uniformly distribute reaction mass
  - Lower stresses
  - Structure well-matched to insert use



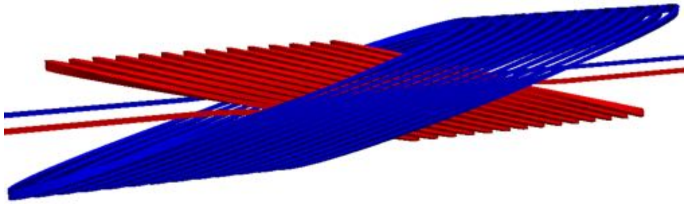
Al - Bronze tubes before machining

BIN4
Total length: **50 cm**





BIN5
Total length: **39 cm**

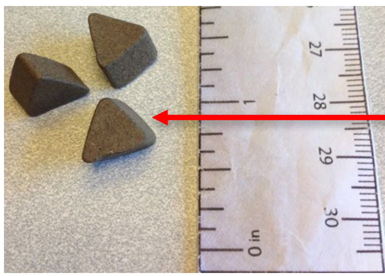


Courtesy T. Shen, L. Garcia Farjado, LBNL

Manufacturing Process of CCT Bi-2212

Manufacturing process of BIN4

1. <u>Mandrel polishing</u>
   - ✓ Sharp edges of the mandrels were smoothed in a polishing tumbler filled up with ceramic pieces during 4 h

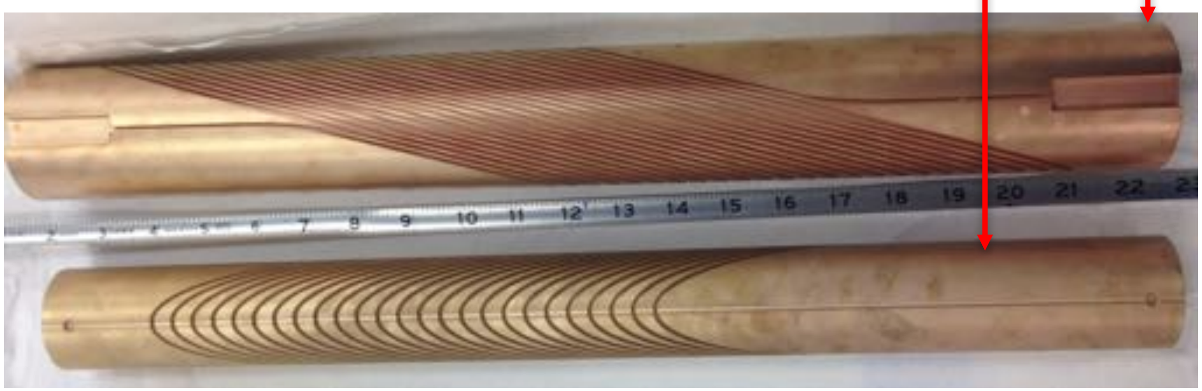


Ceramic points from the tumbler

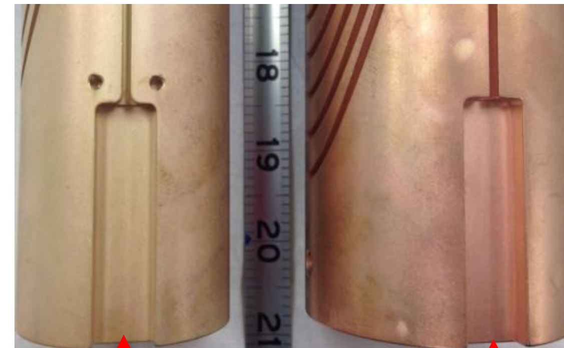
Outer layer

Inner layer

Al - Bronze mandrels after polishing

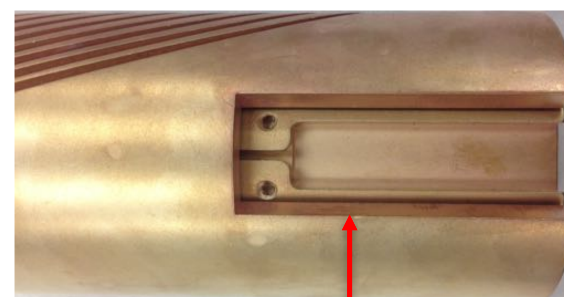


Splice pockets after polishing



Inner layer

Outer layer

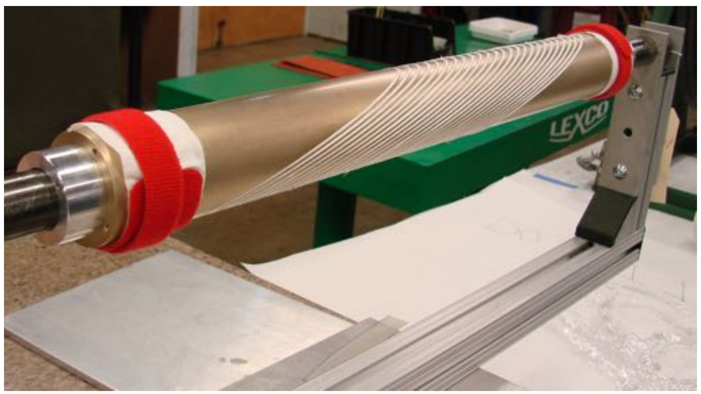


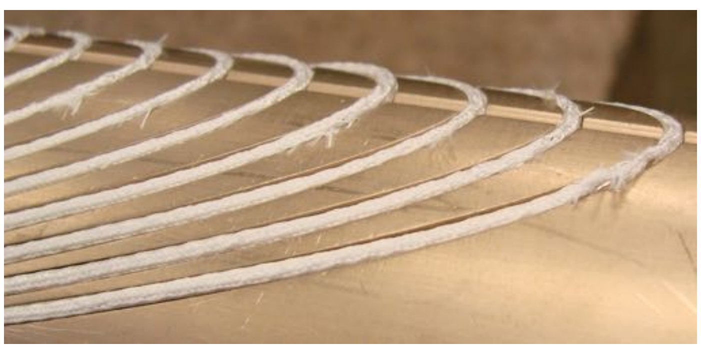
Access to the inner layer after removing windows

L. Garcia Fajardo, LBNL

Coil Winding and Reaction

- Cable insulated with mullite
  - Very brittle, susceptible to damage
  - TiO_2 + sleeve or double layer sleeve
  - Increase channel width in pole region



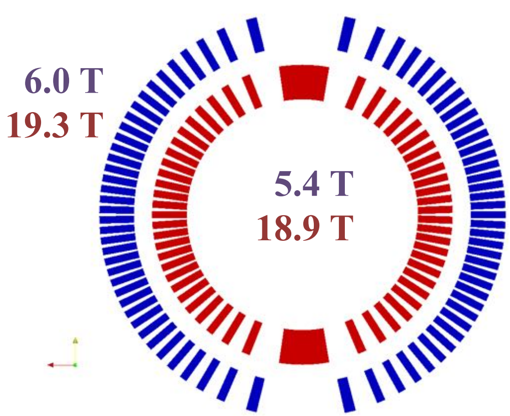


Simple reaction “fixture”

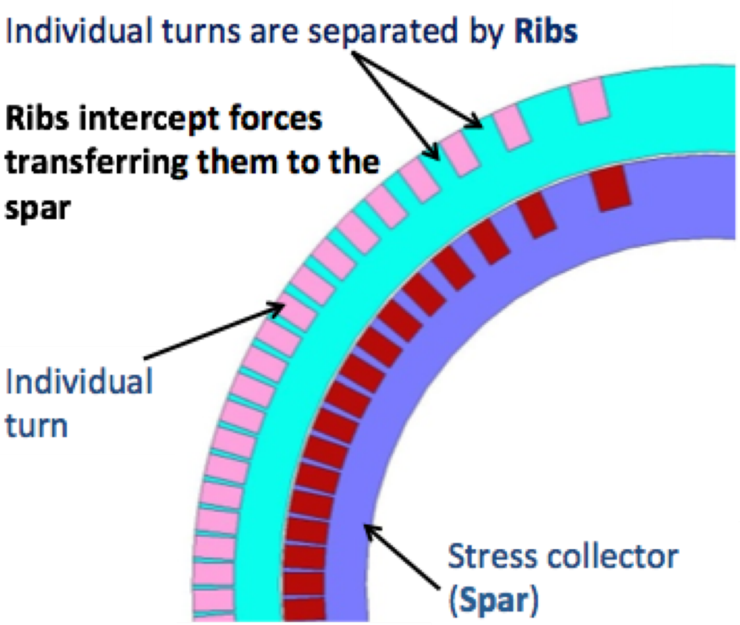
L. Garcia Fajardo, LBNL

Bi-2212 Program Goals

- 5 T as standalone and 3 T in 15 T background field
  - Small outer diameter (to fit outsert)
    - Optimize spar thickness and conductor width
  - Maximize J_e
    - Minimum number of layers
    - Minimize rib thickness
- 2-Layer, 19-strand cable



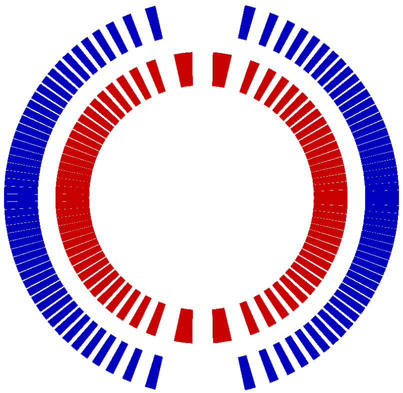
L. Garcia Fajardo, LBNL



S. Caspi, LBNL

Remaining Challenges

- Training at high fields? > 15T
- Quench Detection/Magnet Protection
- Insulation
- Increase efficiency of cross section
  - Modify rib thickness, vary as function of azimuthal angle
  - Or keystoned cable, zero rib thickness
    - 0.72 T/kA closer to cos-theta
  - Much more mechanical analysis
    - Minimize structure and maximize efficiency
    - Keep stress under control



Courtesy L. Garcia Fajardo

EUCARD-2

- EU collaboration partly funded by FP7-European Commission to explore magnet technology in the 16 – 20T range. Focus is development of a 10 kA-class superconducting high current density cable suitable for accelerator magnets.

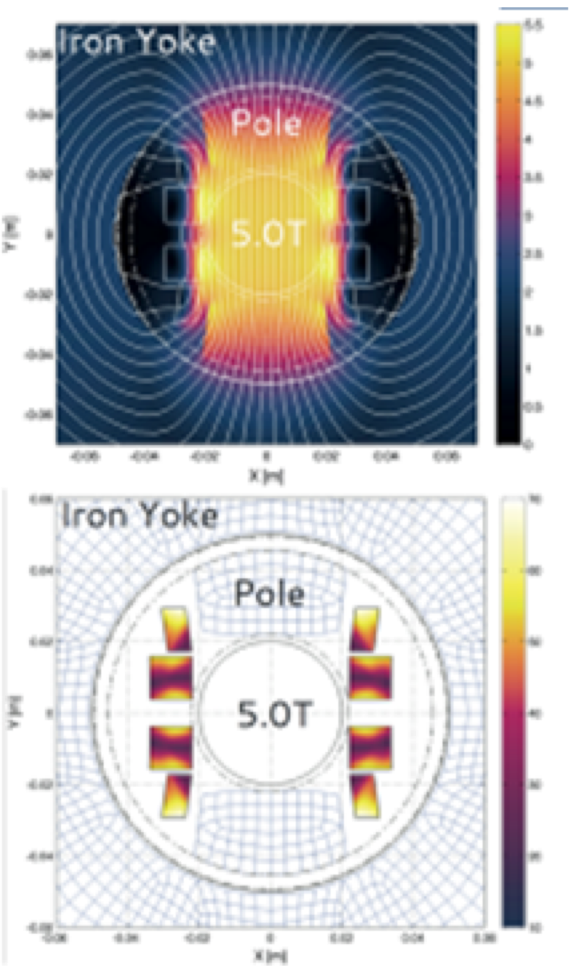
- **Goal**
  - 500 mm long, 40 mm bore, stand-alone magnet of 5 T
  - 15 – 18 T as insert in 12 – 15 T background dipole
  - ReBCO Roebel cables (also considering Bi-2212)

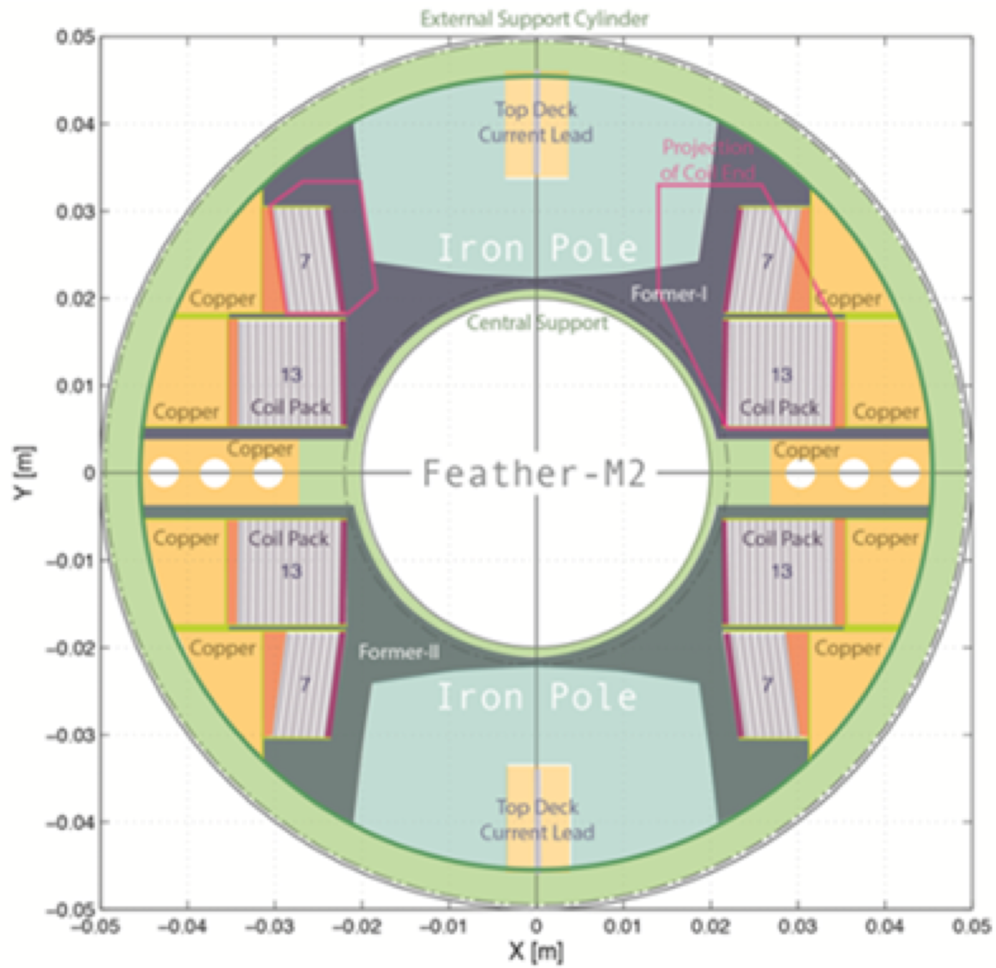
- **First magnet (Feather M2.1-2)**
  - One of the world's first HTS dipoles
  - Reached 3.1 T at 5.7 K
  - No degradation observed
  - Quenched by exceeding critical current, no training

- **Remaining (known) Challenges**
  - Quench detection in liquid He
  - High current joints
  - Field quality (5mm wide tapes)
  - Operation as insert in high background field

G. Kirby, J. van Nugteren, CERN

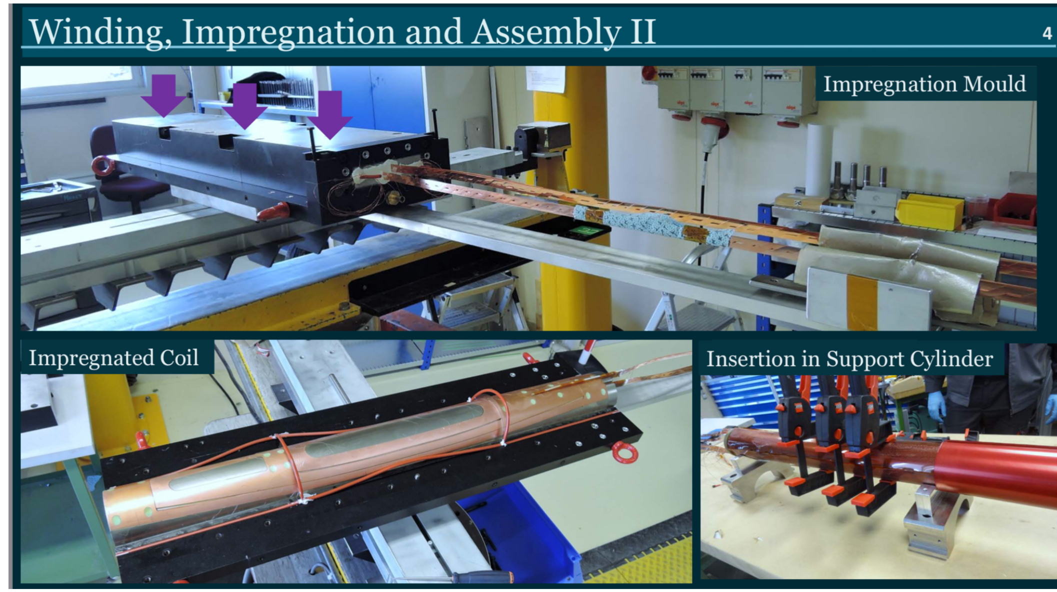
CERN Feather-M2





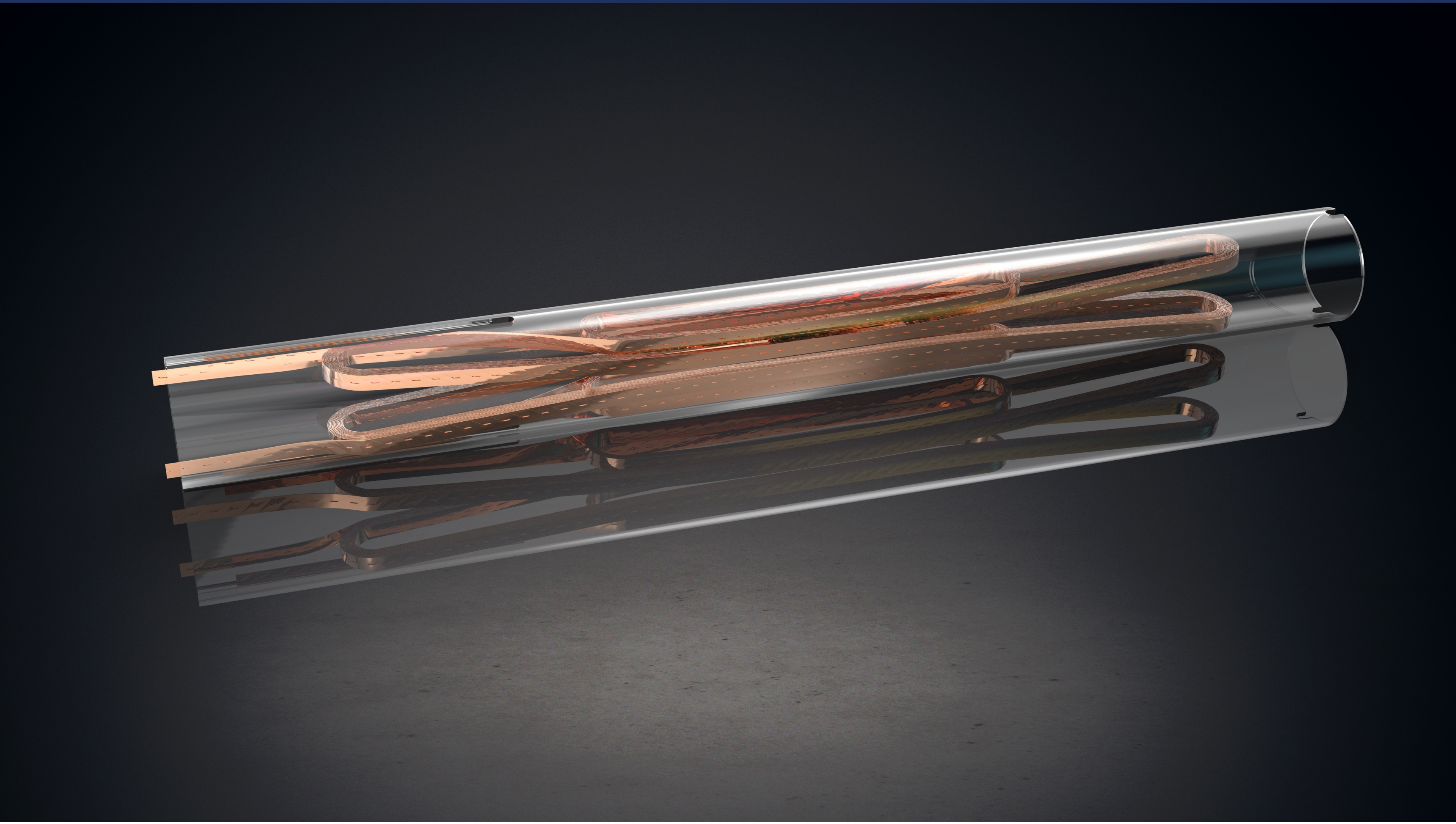
Courtesy Glyn Kirby, CERN

CERN Feather-M2



Courtesy Glyn Kirby, CERN

CERN Feather-M2



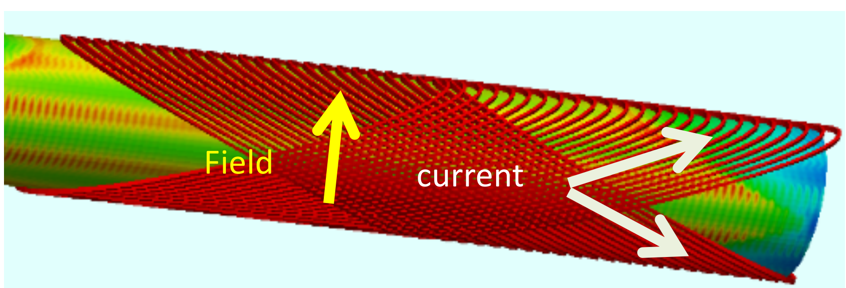
Courtesy Glyn Kirby, CERN

US Magnet Development Program
ReBCO

- Goals

  X. Wang, Program Lead, LBNL

  - Overall
    - Build, test and understand magnet behavior (quite different from LTS)
    - Provide input for conductor development
  - More specifically
    - Initially focus on CORC® and CCT geometry
    - Work toward 5T standalone bore field
    - High field performance as an insert



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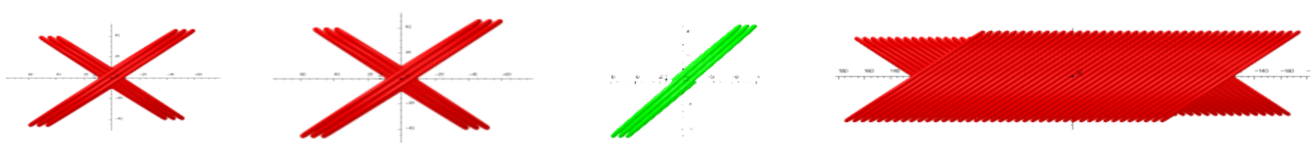
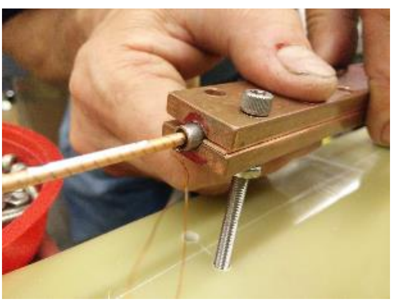
Keeping it Simple

- Start with winding, mandrel fabrication
- Let the techs develop techniques and learn to handle a new material
- Establish a baseline
- Then add features such as leads, quench detection, . . .

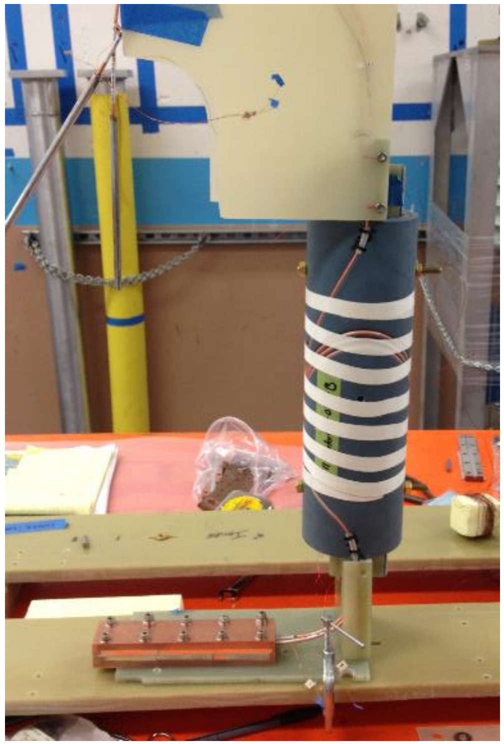


Courtesy X. Wang, LBNL

Winding and Joint Development



Indium foil pressure contact



Praying-hands joint

Courtesy X. Wang, LBNL

Hugh Higley (left) and Andy Lin (right) winding a 40-turn mockup coil

Do not overlook the importance of tech input in all aspects of fabrication and test!

Engaging Conductor Vendors

- Distributing current uniformly to cable from terminals is more challenging than it may first seem.

- Low field, high J_c and rather high contact resistance between tapes opposes current redistribution

J. Weiss and D. van der Laan at LBNL to install terminals

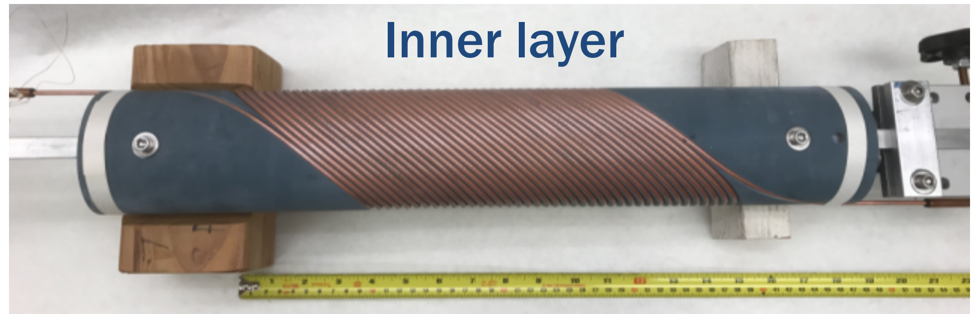
Minimal voids after soldering benefits current transfer

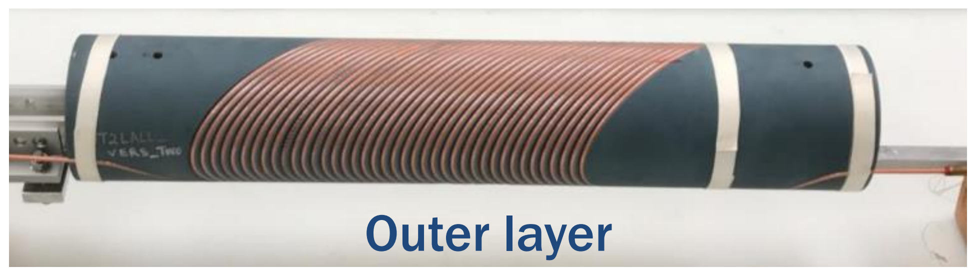
Advanced Conductor Technologies LLC
www.advancedconductor.com

Courtesy X. Wang, LBNL

A 40-Turn Coil: Putting all the pieces together

- Low field (and forces) allow use of 3D printed mandrel in SLA materials. In this case, Blue Stone*
  - No worries about shorts!
  - No impregnation necessary
- Uses 15m of 16-Tape CORC® wire
- Co-wound instrumentation to reduce inductive noise for voltage-based quench detection

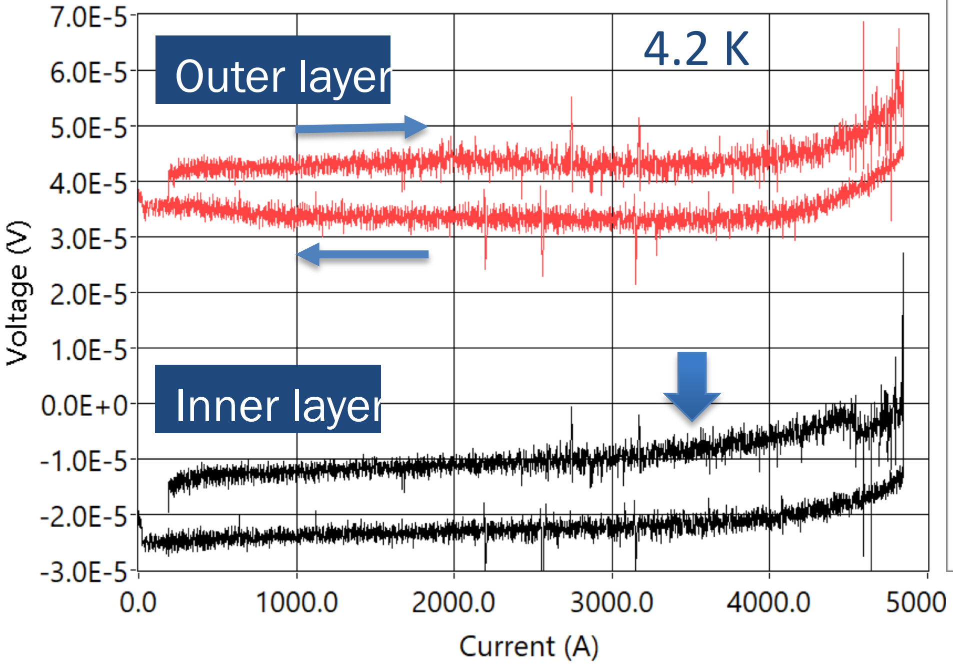


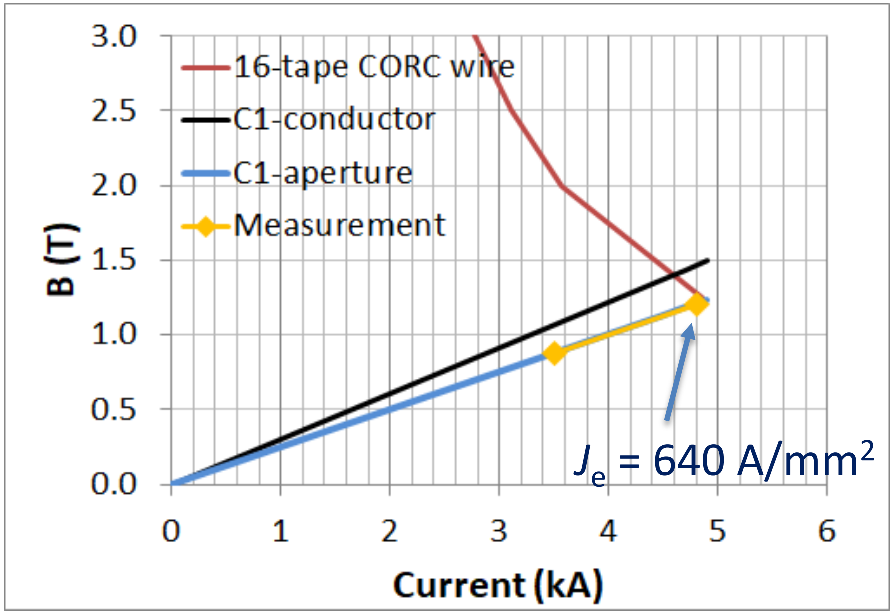


*Ceramic-filled nanocomposite (plastic)

Courtesy X. Wang, LBNL

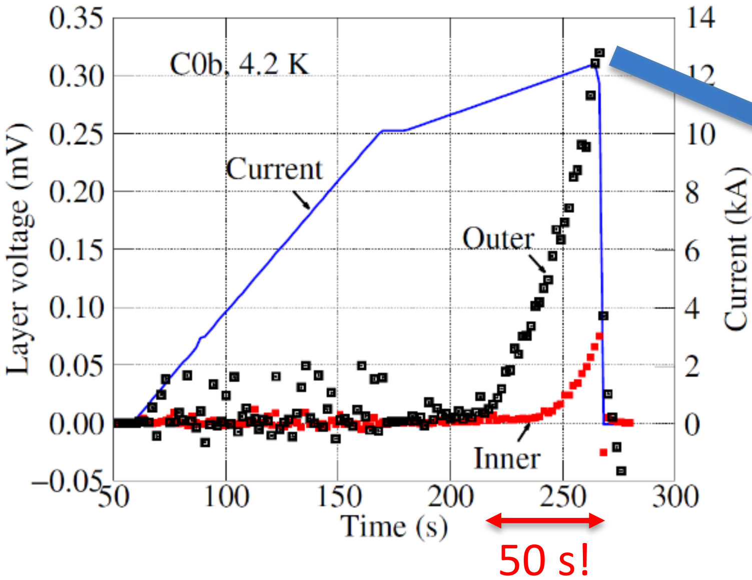
Encouraging Test Results





Transition starts around 3.5 kA (76% of expected short sample) but ultimately reached 104%. Reproducible over several thermal cycles.

Courtesy X. Wang, LBNL



You can also learn from burning things up! Note the duration of the transition. Highly stable conductor is a blessing and a curse.

Courtesy X. Wang, LBNL

So far, the CORC®/CCT route seems promising

Target is 6T in a 15T background field

- Remaining Issues (still quite a few)
  - Je decreases by a factor of 5 from 600 A/mm^2 at 1.4T to 114 A/mm^2 at 20T (That's 0.2 T in a 16T background field)
- Increase J_e
  - Decrease wire diameter (wire J_e)
  - Improve tape J_e
- Increase transfer function
  - More coil layers
  - Reduce wire bend radius
- Current sharing – a necessity
  - Understand and control inter-tape resistance (a dynamic field quality issue as well)

What's Next?

- Hybrids
  - Difficult to separate forces (insert from outsert)
  - Combined – lose higher temperature option
  - Compact geometries like CCT are a natural fit for Bi-2212

- Start to think about all HTS accelerator magnets
  - Active program to develop magnet technology

- Continue to improve cost/performance

Improving Cost/Performance

- High current cables with current sharing
  - Allows use of tapes with defects
  - Increases thermal stability
  - Increases effective piece length
  - Strengthened Bi-2212

- Ultimate goal is to have highest current density in coil pack
  - J_c
  - J_e of tape
  - J_e of cable
  - Reduce anisotropy
  - Increase coil packing fraction

(Mostly regarding ReBCO)

Opportunities (Timing is good!)

- Taking advantage of accelerating development rate and new applications on the horizon. -> non-linear progress
- Performance improvements
  - Higher current density with APC at low temperatures
  - Reduced anisotropy
- Active magnet R&D programs on the verge of demos that will stimulate the environment
- Fusion Energy Sciences moving back to some technology development

Biggest obstacle to progress is access to conductor in quantity

Opportunities in Fusion

- Fusion Energy Sciences Technology Advisory Committee (FESAC) subpanel on Transformative Enabling Capabilities (TEC)
  - A large number of topics examined including HTS for high field, high operating temp magnets for magnetic confinement fusion
  - Report just completed and is now available on the FESAC webpage: https://science.energy.gov/fes/fesac/reports/
  - HTS was chosen as one of four "Tier 1" TECs. "Most Promising"
- Performance goals common with HEP will increase opportunities
  - High current cables under high stress conditions

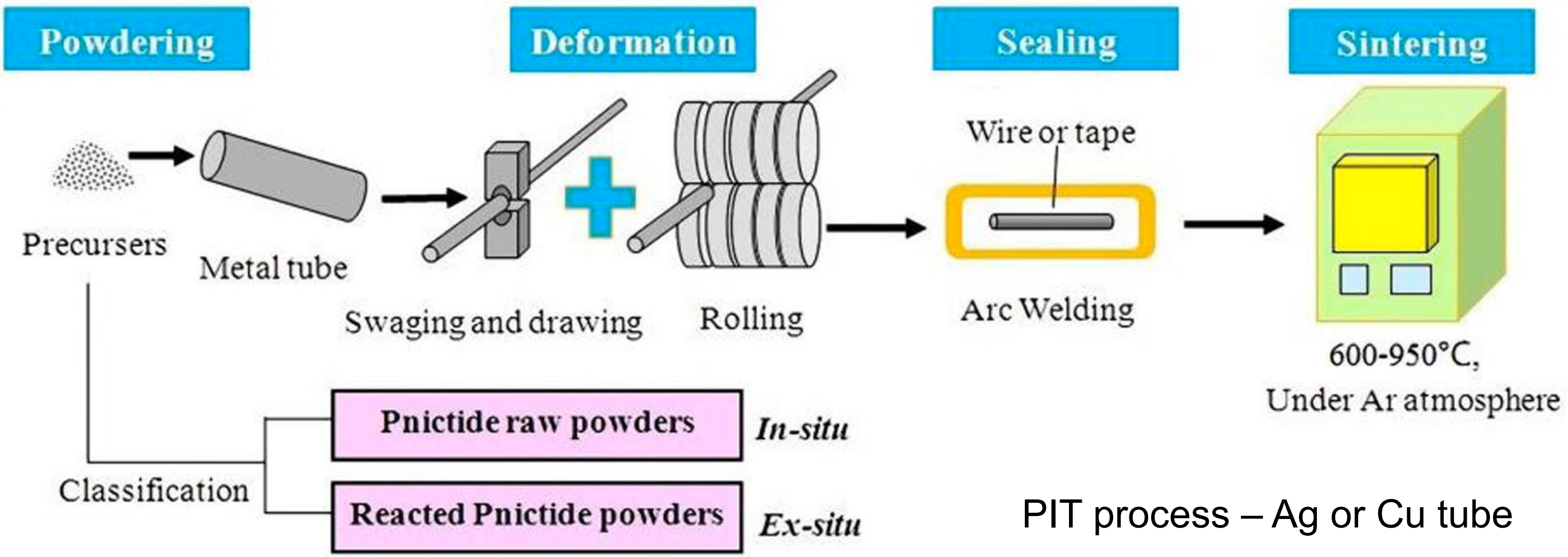
Creating a New Paradigm

- Look to near term demos of technology feasibility to help create/drive a sustainable market.
  - Development of high current cables is critical
  - Explore magnet geometries
  - Provide platforms for Quench Detection concept development
- Other applications outside HEP/Fusion (ion sources, undulators, gantries, solenoids, NMR, 25T solenoids for x-ray and neutron facilities . . . and wind turbines
- Upshot
  - Development of a new enabling capability is key to adoption of any new technology (regardless of cost)
  - Stop worrying about cost and make more magnets!

Iron-Based Superconductors (IBSCs)

- Sr/$BaFe_2As_2$:K (T_c = 38 K, 122 type)
- Among 4 compounds, the 122 type is the most relevant for applications because of its ultrahigh H_{c2} > 70 T at 20 K
- So, what's the excitement about?
  - Potentially low cost
    - Materials are cheap (except maybe for the silver) and fabrication is easy
  - Low anisotropy
  - Similar strain sensitivity as Bi-2212
  - J_c's reaching practical levels (well, almost)
    - > 10^3 A/mm^2
  - Main Issues
    - Significantly raise J_c
    - Manufacturing
    - Toxic?

High transport current superconductivity in powder-in-tube Ba0.6K0.4Fe2 As2 tapes at 27 T He Huang et al 2018 Supercond. Sci. Technol. 31 015017



PIT process – Ag or Cu tube

Hideo Hosono[1,2] Akiyasu Yamamoto[3] Hidenori Hiramatsu[1,2] Yanwei Ma[4], "Recent advances in iron-based superconductors toward applications," https://www.sciencedirect.com/science/article/pii/S1369702117306545

Cost

- HEP is not driving the development of HTS though there is a modest amount of funding steering the R&D (DOE HEP and EERE)

- Currently only one producer of Bi-2212 wire and two powder producers

- Historical note: Aluminum was very expensive at first too!

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